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(6) HUMAN AND COMPUTER CONTROL
OF UNDERSEA TELEOPERATORS,

(9) [illegible]

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) This is a review of factors pertaining to man-machine interaction in remote control of undersea vehicles, especially their manipulators and sensors. Emphasis is placed on human operator control of such teleoperator systems as a function of degree of automation sensor-control integration and task demands for underwater search, object recovery and manipulation. Models of operator-computer performance are considered, particularly with respect to human supervisory control of semi-autonomous systems.

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Sections of the report discuss: teleoperated submersible vehicles or work platforms; undersea tasks and how they can be analyzed; relative roles of human and computer or other control elements; control hardware (sensors, communication, propulsion, manipulation, control station) and how it affects the human controller; control software for computer-aided manipulation, including a review of various languages and algorithms presently available; human operator performance in manipulator control (a review of what we now know); present and prospective theoretical models of supervisory control; and finally, the needs for research in this area.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF FIGURES (continued)

LIST OF TABLES

1. INTRODUCTION

1.1 Teleoperators and Supervisory Control

This study is neither an experimental research report nor a survey in the usual sense. It is, rather, a broad examination of future undersea tasks the U. S. Navy faces and the potential for their accomplishment by "teleoperators". We define teleoperators to be general purpose submersible work vehicles controlled remotely by human operators and with video and/or other sensors, power and propulsive actuators for mobility, with mechanical hands and arms for manipulation and possibly a computer for a limited degree of control autonomy. A manned submersible is not a teleoperator vehicle, but the attached manipulators are certainly teleoperators, requiring control through a viewing port or through closed-circuit video. Sometimes the term "teleoperator" is restricted to telemanipulator, excluding the system for remotely positioning and orienting a sensor, but for the sake of generality we include this important function.

This study focuses on those aspects of undersea teleoperation which concern the human operator and the man-machine interface, and within this still relatively broad domain, it concentrates on the prospects for utilization of "supervisory control". Supervisory control is a hierarchical control scheme whereby a system (which could be a teleoperator, but could also be an aircraft, power plant, etc.) having sensors, actuators and a computer, and capable of autonomous decision-making and control over short periods and in restricted conditions, is remotely monitored and intermittently operated directly or reprogrammed by a person.

The distinction between direct human control of a teleoperator and supervisory control of a teleoperator is made graphically in Figure 1.1. In the upper figure the human directly controls, over either a wire or sonic communication link, the separate propulsive actuators of the vehicle, the actuators for the separate degrees of freedom of the manipulator, and the pan and tilt actuators of the video camera. The video picture is sent back directly to the operator. The "hand control" can be a master-slave positioning replica or a rate joystick.

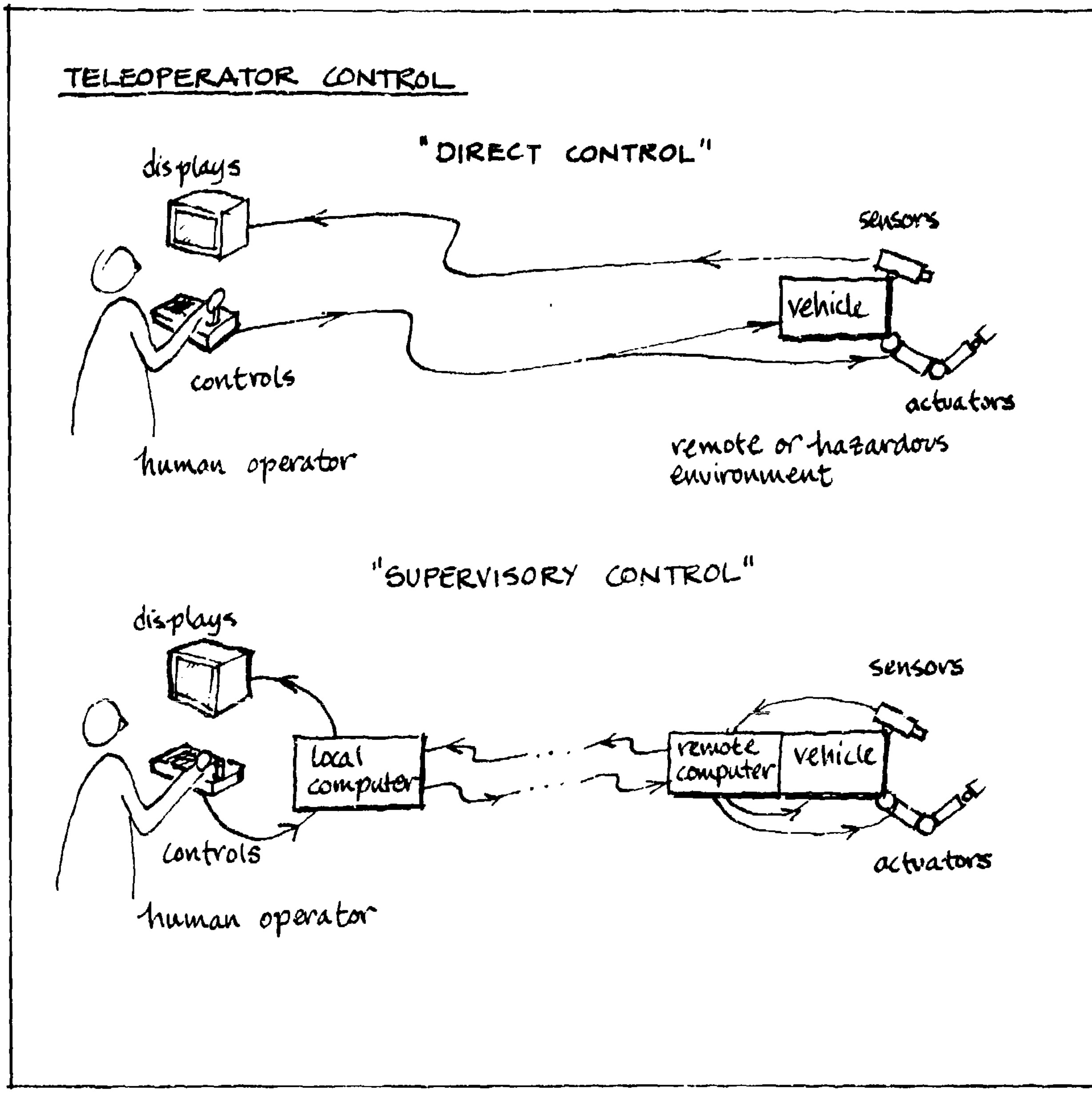


FIGURE 1.1 DIRECT AND SUPERVISORY CONTROL OF A TELEOPERATOR: DEFINITIONS

TELEOPERATOR: A vehicle having sensors and actuators for mobility and/or manipulation, remotely controlled by a human operator, and thus enabling him to extend his sensory-motor function to remote or hazardous environments.

SUPERVISORY CONTROL: A hierarchical control scheme whereby a (teleoperator or other) device having sensors, actuators and a computer, and capable of autonomous decision making and control over short periods and restricted conditions, is remotely monitored and intermittently operated directly or reprogrammed by a person.

In the lower figure a computer is added to the teleoperator, and for short periods and limited circumstances this teleoperator can function autonomously.

At the bottom are generic definitions of teleoperator and supervisory control. The upper drawing portrays the former without the latter. The lower drawing is the combination.

In supervisory control the teleoperator's (remote) computer communicates at high bit-rate with the teleoperator's sensors and actuators. But because of bandwidth constraints on the signal transmission link, or because of teleoperator sensing limitations, communication may be restricted to low-bit-rate with the human operator's (local) computer. For this reason, and also because of the intermittent nature of human monitoring and reprogramming of commands on a keyboard (and possibly joystick or other controls), the human supervisor's communication with the teleoperator tends to be at a slow rate, i.e., intermittent symbol strings or movement sequences on a master-controller with relatively many bits per instruction package. His communication with the local computer to refresh TV images or to edit or "dry run" his commands on a model before commiting them to action may be constrained only by his own speed limitations. The details of supervisory control are discussed more thoroughly in succeeding sections of this report.

The physical separation of local and remote computer is not necessary in aircraft, industrial plants or other systems where the operator is physically nearby, and where supervisory control is used for reasons other than physical remoteness and limited communication channel capacity between human operator and the object of control. In such situations supervisory control may be advantageous, nevertheless, to achieve faster or more accurate control, or to control simultaneously in more degrees-of-freedom than the operator can achieve by direct servo-control, or to relieve him of tedium. The latter reasons for supervisory control can apply to undersea vehicles when the human operator is not physically distant (as with manned submersibles) or to undersea teleoperators when a reliable high-bandwidth communication channel (wire or optical tether) is available.

1.2 Why Teleoperators Underseas? The Limits of Divers and Manned Submersibles

The principal reasons for interest in using teleoperators for undersea tasks are dollar costs and safety.

Operations, including exploration, inspection, construction, maintenance, salvage and rescue, are having to be performed at increasing depths. At such depths - below, say 300 m. (depending upon the particular task) the time required for divers - mostly compression/decompression time - becomes excessive; factors having to do with depth per se including life support equipment become increasingly costly; personal safety is more and more difficult to maintain. These assertions are borne out by rather alarming mortality figures for commercial divers in the North Sea.

Figures 1.2 and 1.3 give further indication of the problem. Water turbidity and other depth-related factors may require greater bottom-time, thus compounding the decompression-time factor. Under such conditions, a fixed-capability teleoperator, which sometimes is seen as too clumsy by comparison to a human diver at shallower depths, becomes much more attractive economically.

Happily, there is progress in the development of teleoperators, and they are becoming less clumsy. Inspection and manipulation tasks which simply could not be accomplished a few years ago are now achievable, due to steady progress in the design of video systems, mechanical valves and actuators, etc. For the immediate future, however, the primary technological factor which is changing the prospects for undersea teleoperation is the computer.

Circa 1970, divers seemed to have the edge on manned work-vehicles with manipulators in terms of maneuverability, manipulation, tactile sensing, and covertness. Because of smaller unmanned vehicles and eventually through unmanned untethered vehicles, however, the diver (especially the tethered diver) is losing his edge. Manipulation, sensing and cognition remain the primary advantages for the diver, but the computer is changing these also.

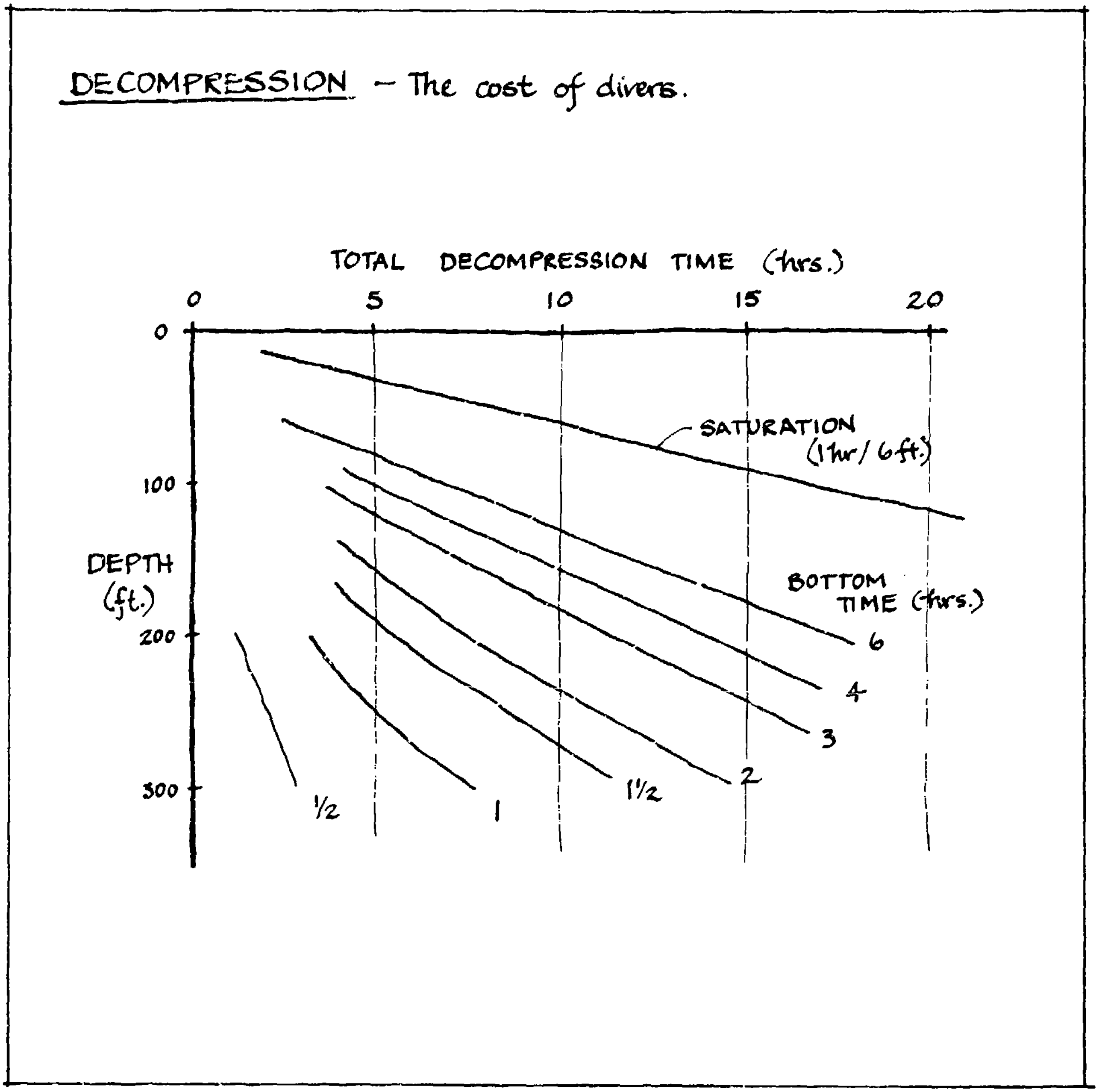


FIGURE 1.2 DECOMPRESSION TIME REQUIRED BY A HUMAN DIVER is one of the major penalties and costs of diving at ambient pressures (Shilling, 1976). At first, the longer the time spent at a particular depth (bottom time) the longer is the time spent in decompression. After enough bottom time the blood becomes saturated with dissolved gases and the decompression time is then just a function of depth (approximatly 1 hour for every 6 feet).

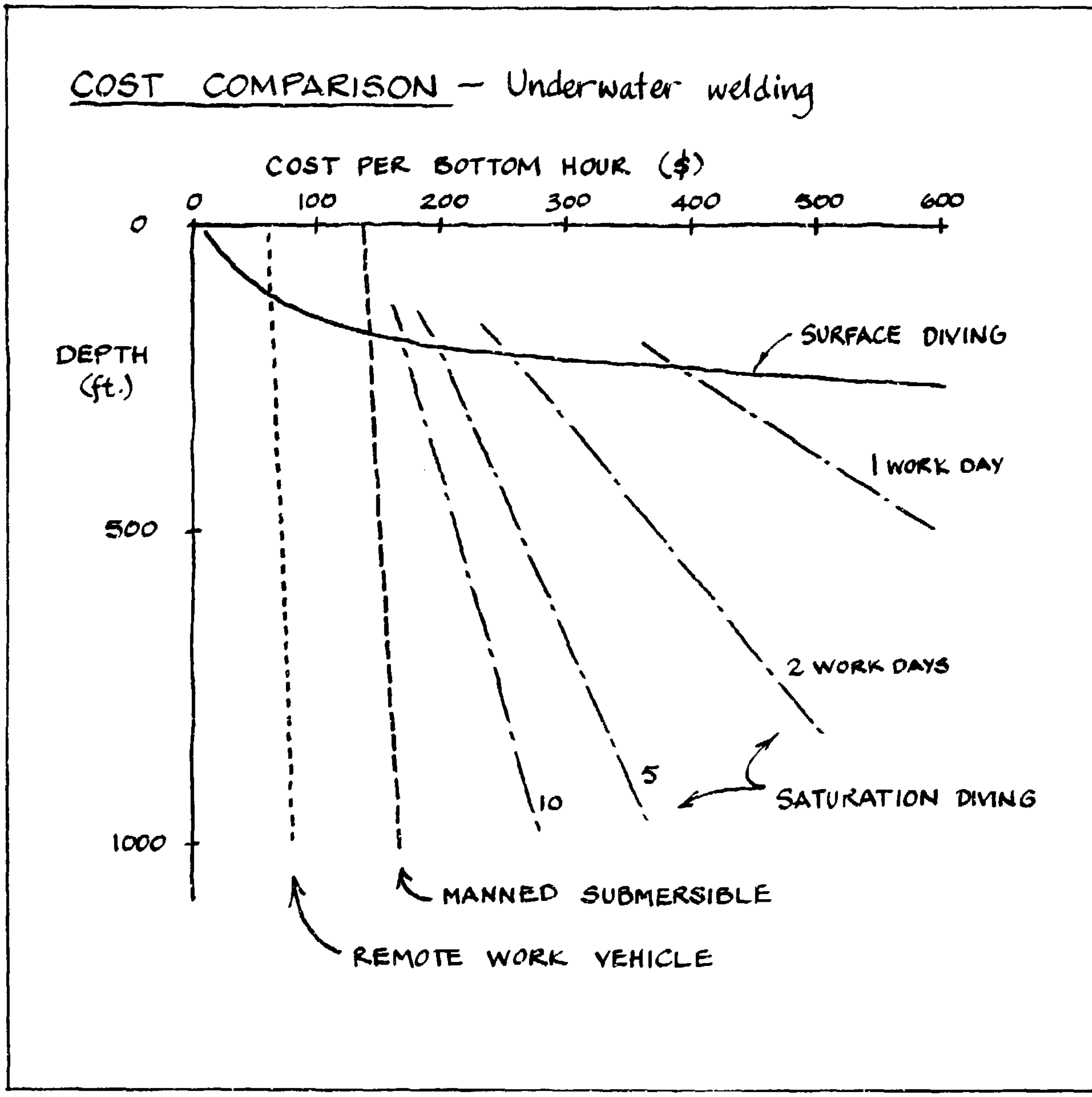


FIGURE 1.3 COST COMPARISONS OF VARIOUS MEANS FOR UNDERWATER WELDING were estimated by Moore (1975). Note that the per-hour cost of saturation diving is reduced for longer dives because the time for decompression is a smaller portion of the total. The choice of diver, manned or unmanned submersible will also depend on their productivities; if it takes the remote work vehicle twice as long to accomplish the same task it has no cost advantage over the manned submersible.

The comparison between teleoperators and manned submersibles is more clear-cut. The fact is that television cameras can now "see" with less light than the human eye, and new sonic imaging systems can see through densely turbid waters where neither human vision nor video can function. Spatial resolution of video can be made to approximate that of the eye by focusing. Present advantages of manned submersibles or teleoperators as work vehicles (neglecting for the moment personnel rescue) are: steropsis for close-up objects, and the ability of a human observer with a wide angle of view to keep track of the relative location of different objects. As the communication channel improves, to the point where the manipulator itself is the limiting factor, a man at the surface can control manipulators or video pan-tilt controls just as well as a man in a submersible. The major differences remaining between manned submersible and teleoperator are then cost and safety, as with the diver. The pressure vessel and life-support equipment make the manned submersible much more costly than the same vehicle without the pressure vessel and life-support equipment but with remote control instead. The factors of quality and reliability of communication and remote control then become the key factors; these are discussed in subsequent sections.

1.3 Why Supervisory Control of Teleoperators Underseas? Progress in Microelectronics and Computer-Control Software.

At the authors' own institution just 25 years ago, the Whirlwind 1 computer filled a 2 1/2 story brick building. Today the equivalent computational capacity is available in a single microelectronic chip. The implications of this technological change for undersea capability are immense.

Physical size has decreased to the point where, in comparison to other physical components required for a teleoperator, the space requirement is negligible. The power requirements of microelectronics, by compairson to those required for propulsion, sonic communication and other possible needs, are also close to negligible. Computing speeds have increased also,but not so dramatically as size and power. But the most dramatic change of all has been in cost.

Concomitant with these hardware changes, primarily cost, have been equally dramatic developments in computer software, including "systems architecture", "pattern recognition" and "artificial intelligence". The implications of these for underseas operations are probably less well understood, but the hardware changes without the software changes would not make the potential for teleoperation nearly so great.

It is probably true that much of the sophisticated computer research now being carried out in academia has questionable immediate practical value here so long as a human operator is in the control loop with fairly satisfactory communication from and to the teleoperator, and he can get reasonable visual images at least intermittently and control the vehicle and its arms, if it has any, with fair precision.

But the point is that potential for computer control, with even modest degrees of pattern recognition and artificial intelligence, is just beginning to be understood. This report is intended to aid that process.

In the next section we review some of the bibliographic sources on the history of teleoperators, not only as applied to undersea problems, but also as applied to nuclear operations, space, and the industrial production line.

In subsequent sections we restate some assertions about the problem, specify the purposes of our present study, and discuss our framework for dealing with these problems and purposes in this report.

1.4 History of Teleoperators

The first concerted work on teleoperators was done by the U. S. Atomic Energy Commission during the late 1940's and early 1950's, and located primarily at the Argonne National Laboratory near Chicago within a group headed by Raymond Goertz. This early work (Goertz, 1954) culminated in the "model 8" tape/cable-connected master-slave "through-the-wall" manipulator, still much used and still being manufactured in modified form for the nuclear industry, and the E-1, 2, 3, 4 series of force-reflecting electrical-servo-controlled master-slave manipulator with controlled articulations in the

fingers as well as the hand. About the same time General Mills, American Machine and Foundry, and the Unimation Co., were starting their manipulator developments.

The U. S. Navy, at the University of California in La Jolla, began its involvement with teleoperators by developing the Remote Underwater Manipulator (RUM), a servo-manipulator attached to a bottom crawling work platform which played out its own control cable as it went into the water. By the end of the 1950's the early research submersible, Trieste, had been equipped with a manipulator, and other groups were planning to augment their submersibles in similar fashion.

This early history of teleoperators (or "telechirics", an alternative term which was also in fashion at the time) is recounted in a number of sources, including reports by USAEC (1964), Johnson and Corliss (1967), Corliss and Johnson (1968), Johnson and Magee (1969), Gavrilovic and Wilson (1970). More recent conferences on remotely manned systems are reported in proceedings edited by Heer (1973, 1975), and others. In the last two years, a number of teleoperator conferences have been sponsored by professional societies, including the Institute of Electrical and Electronic Engineers, the Society of Manufacturing Engineers (and its offshoot, the Robot Society of America), and various international societies such as the International Federation for the Theory of Machines and Mechanisms.

1.5 Summary of Assertions about the Problem

We now summarize our principle axioms or assertions about the problem:

1. Demands are increasingly stringent in terms of depth, sensory resolution, speed and accuracy and power of response for accomplishment of undersea tasks. Some of these tasks are always the same and are amenable to fixed automation, but many are different each time they occur and therefore cannot be done by fixed automation.
2. In terms of depth and skill human divers are reaching their limits, or when they go beyond these limits they do so at significant risk to life and cost in support equipment and personnel.

3. Teleoperators, i.e., submersibles having video and other sensors, actuators for mobility and manipulation, and remotely controlled by human operators, offer much promise for extending man's flexible, adaptable, perceiving and control capabilities into remote and hazardous environments.
4. Present teleoperators are quite limited in sensory capability (e.g., in turbid water), in manipulation capability (in speed and dexterity as compared to human hands), and in dealing with distortion in man-machine communication (misorientation of teleoperator to human body, time delays and noise).
5. Computers are rapidly getting smaller in size and power requirement and cheaper in cost for a given computing capability.
6. While accomplishment of one-of-a-kind undersea tasks by intelligent and completely autonomous robots may have appeal, we simply do not have available at this time such devices or the understanding to build such devices.
7. Undersea systems, like aerospace systems, demand conservative design because unreliability poses severe costs.
8. The most immediate and reliable approach would appear to be to add modest computer aiding and "artificial intelligence" to teleoperators, retaining human sensing, motor, memory and decision capability, at least for higher level planning, decision-making,and control.
9. Over a longer period of years, as computer control and artificial intelligence become more sophisticated, certain human functions in teleoperation may be replaced, but greater need and demand will be placed upon other human functions, and in these respects the need for improved man-computer interaction will increase, not dimish.

1.6 Purposes of This Study

We now summarize our purposes in this study:

1. Survey and analyze undersea tasks appropriate to accomplishment by teleoperators.
2. Analyze constraints in the undersea environment and technological constraints of submersible vehicles, communication and control systems which most significantly mediate teleoperator control - primarily the man-machine aspects.

3. Investigate and define theories of operator control performance applicable to remotely controlled systems. Develop taxonomic and mathematical models of man-machine interactions in undersea teleoperation (inspection, vehicle control, manipulation), particularly those pertaining to supervisory control - where man controls computer on slow time scale while computer controls teleoperator on fast time scale.
4. Recommend specific laboratory simulation experiments with human subjects and software developments to explore and demonstrate various supervisory control modes, and measure teleoperator performance.
5. Perform some of the above experiments and apply some of the above models. (This is planned for follow-on phases of the present contract.)

1.7 Framework for Organization of the Report

In Section 2 different types of existing undersea vehicles are classified, using taxonomies or classification schemes which serve to illustrate the influence of several key control variables, such as: size and weight; whether it is manned or unmanned; what tasks it is designed for; etc. Hypothetical vehicles are also considered, and it is evident that the unmanned, untethered vehicle is a gap.

Section 3 classifies those undersea tasks which teleoperators presently or in the future can be called upon to perform. Various methods of task analysis are illustrated by the techniques several authors have used to analyze undersea tasks. The major lessons which are emerging from these task analyses are reviewed.

Section 4 deals with the problem of control in a general way; what it is and what are the prospects for both human and computer contributions to control.

Section 5 discusses alternative control system hardware configurations from the viewpoint of their interaction with the human operator for: sensing communication, display, vehicle mobility, manipulation, command.

In section 6 we review and discuss various computer languages and decision aids for supervisory control, and generalize on the important human factors which affect their design.

Section 7 discusses problems and methods for measuring and evaluating human operator performance in teleoperator control, citing various examples from the literature to indicate the status of understanding here.

Section 8 discusses theory and quantitative models pertaining to the man-machine aspects of teleoperator control, particularly supervisory control of teleoperators.

Finally, section 9 presents a list of important research needs pertinent to undersea teleoperators, and, in particular, to supervisory control of undersea teleoperators.

2. TELEOPERATED VEHICLES

The purpose of this section is, first, to indicate the range of undersea vehicles which presently exist and how they vary with respect to certain key variables which affect their control. Secondly, and by contrast to what presently exists, we discuss the possibility for unmanned, untethered supervisory-controlled vehicles (teleoperators).

2.1 Present Undersea Vehicles

Table 2.1 is a listing of unmanned (remotely manned) undersea vehicles indicating name, operator, depth and weight. Most of the data are from Vadus (1976). While we have added more recent vehicles known to us, we do not claim this to be a comprehensive list.

Table 2.2 is a listing of manned vehicles, also from Vadus (1976).

The key variables indicated which concern control and apply to the subsequent sections of this report are

1. whether a vehicle is manned or unmanned
2. its design depth
3. its size and weight
4. whether it is tethered or untethered
5. whether it carries its own power source (even if tethered)
6. what its speed and operating endurance are (these are related)
7. what sensors and manipulators it carries

Figure 2.1 illustrates a rather interesting differentiation between manned and unmanned vehicles in terms of weight and depth. As depth of manned vehicles increases weight also increases due presumably to required additional strength of the pressure vessel. The weight of unmanned vehicles is not so sensitive to depth, and there is more variability in weight, the primary determiner of weight being the function. Note that unmanned vehicles numbered 24, 25 and 45, which are special-purpose heavy-duty work vehicles, are exceptions to the unmanned cluster, and that "JIM" (50), the atmospheric diving suit , is a sole exception to the manned cluster.

TABLE 2.1 UNMANNED SUBMERSIBLES,(Vadus,1976)

	NAME	OPERATOR	DEPTH (ft.)	WEIGHT (lbs.)
1	BATFISH	Bedford Inst.,Can.	650	154
2	PAP	Societe ECA, Fr.	600	1,760
3	ROBOT	Mitsubishi Ind., Jap.	800	3,530
4	TELENANTE I	Inst. Fr. Petro.	1,000	2,200
5	TELENANTE II	Inst. Fr. Petro.	1,000	2,200
6	TROV	Canada Center Inland Waters	1,200	1,300
8	TROV I	Underground Loc. Serv.	1,200	2,000
9	TROV II	McElhanney Offshore	1,200	1,200
10	EL SNOOPY	Nav. Ocean Sys. Ctr.	1,500	150
11	EL SNOOPY	Nav.Fac.Engr.Cen.	1,500	300
12	RECON II	Perry Oceanog.	1,500	450
13	CORD	Harbor Br. Found	1,500	770
14	UARS	Univ. of Washington	1,500	900
15	SCAT	Nav. Ocean Sys. Ctr.	2,000	400
16	CONSUB	Inst.of Geology,U.K.	2,000	1,760
17	DEEPDRONE	Ametek Straza	2,000	5,000
18	RUFAS II	Miss. State Univ.	2,400	1,000
19	CURV IIB	Nav. Torpedo Sta.	2,500	3,000
20	CURV II	Nav. Ocean Sys. Ctr.	2,500	3,450
21	SCORPIO	Ametek Straza	3,000	1,500
22	SKORPENA	U.S.S.R.	3,300	1,000
23	ERIC	French Navy	3,300	4,410
24	WORK VEH	HYDROTECH	4,000	40,000
25	VERT.TRANS. VEH.	HYDROTECH	4,000	100,000
26	RCV 225	HYDROPRODUCTS	6,600	180
27	RCV 150	HYDROPRODUCTS	6,600	1,000
28	SORD I	Naval Torpedo Sta.	6,500	4,000
29	SORD II	Naval Torpedo Sta.	6,500	4,000
30	SCARAB	A.T.&T. Co.	6,000	5,000
31	DOWS	Ametek Straza	6,000	5,000
32	CURV III	Nav. Ocean Sys. Ctr.	7,000	4,500
33	TROIKA	DCAN, Fr.	7,220	2,000
34	RUM/ORB	Scripps Inst.	8,000	24,000
35	NEDAR I	Assoc. Marine Ser.	10,000	2,400
36	KRAB-1	Acad. Sci., USSR	10,000	1,000
37	SPURV	Univ. of Wash.	12,000	1,000
38	DEEP TOW	Scripps Inst.	20,000	324
39	MIZAR FISH	Nav. Res. Lab.	20,000	4,300
40	UDOSS	Jet Prop. Lab.	20,000	3,000
41	SEA DRONE I	Pre Con Inc.	20,000	2,800
42	TELEPROBE	Nav. Oceanog. Off.	20,000	3,500
43	RUWS	Nav. Ocean Sys. Ctr.	20,000	4,300
44	NEDAR II	Assoc. Marine Ser.	25,000	1,800
45	SEA PROBE	Ocean Search Inc.	10,000	400,000

TABLE 2.2 MANNED SUBMERSIBLES(Vadus,1976)

	NAME	OPERATOR	DEPTH (ft.)	WEIGHT (lbs.)
1	NEMO	SW Research Inst.	600	2,000
2	SEA EXPLORER	Sea Line Inc.	600	3,600
3	PC-3B	Int'l V.W. Contr.	600	6,350
4	SEA RANGER	Verne Engr. Corp.	600	19,000
5	NEKTON ALPHA	Gen. Oceanographics	1,000	4,500
6	NEKTON BETA	Gen. Oceanographics	1,000	4,700
7	NEKTON GAMMA	Gen. Oceanographics	1,000	4,700
8	PC-8	Intersub	800	11,000
9	SEA RAY	Sub R&D Corp.	1,000	9,000
10	OP SUB	Ocean Systems	1,000	10,400
11	AQUARIUS	HYCO Subsea	1,100	11,000
12	PC-14	Army Missile Com.	1,200	10,000
13	STAR II	Deepwater Expl. Ltd.	1,200	10,000
14	MERMAID	Int'l U.W. Contr.	1,000	14,000
15	MOANA	COMEX	1,300	20,000
16	SEA OTTER	Arctic Marine	1,100	6,300
17	DEEPVIEW	SW Research Inst.	1,500	12,000
18	PISCES I	Vickers Oceanics	1,500	15,000
19	PC-9	P & O Subsea	1,350	22,500
20	PC-17	Perry Oceanog.	1,500	38,000
21	DEEPSTAR	G.O. Int'l.	2,000	15,000
22	SEA LINK II	Harbor Br. Found.	2,000	21,000
23	SDL-1	Canadian Navy	2,000	30,000
24	BEAVER IV	Int'l. V.W. Contr.	2,700	34,000
25	AUG.PICCARD	Horton Maritime	2,500	360,000
26	PC-16	InterSub	3,000	33,000
27	PISCES II	Vickers Oceanics	2,400	24,000
28	PISCES VIII	Vickers Oceanics	3,000	24,000
29	PISCES III	Vickers Oceanics	3,000	24,000
30	DEEPSTAR 4000	COMEX	4,000	18,000
31	DSRV I	U.S. Navy	5,000	75,000
32	DSRV II	U.S. Navy	6,500	75,000
33	DOWB	G.M.	6,500	20,000
34	PISCES VI	HYCO Subsea	6,600	24,400
35	PISCES IV	Dept. of Environ.	6,600	24,100
36	PISCES V	HYCO Subsea	6,600	24,400
37	PISCES IX	HYCO Subsea	6,600	24,400
38	SEA CLIFF	U.S. Navy	6,500	42,000
39	SEA TURTLE	U.S. Navy	6,500	42,000
40	DEEPQUEST	Lockheed	8,000	115,000
41	ALVIN	Woods Hole O.I.	12,000	32,000
42	TRIESTE	U.S. Navy	20,000	180,000
43	ARCHIMEDE	CNEXO	36,000	122,000
44	PC-12(01)	InterSub	1,000	18,000
45	PC-12(03)	COMEX	1,000	18,000
46	SEALINK I	Harbor Branch Found.	1,000	21,000
47	VOL-L1&L2	Vickers	1,200	28,000
48	PC-12(02)	InterSub	1,000	33,000
50	JIM	Oceaneering Int'l.	1,300	1,100

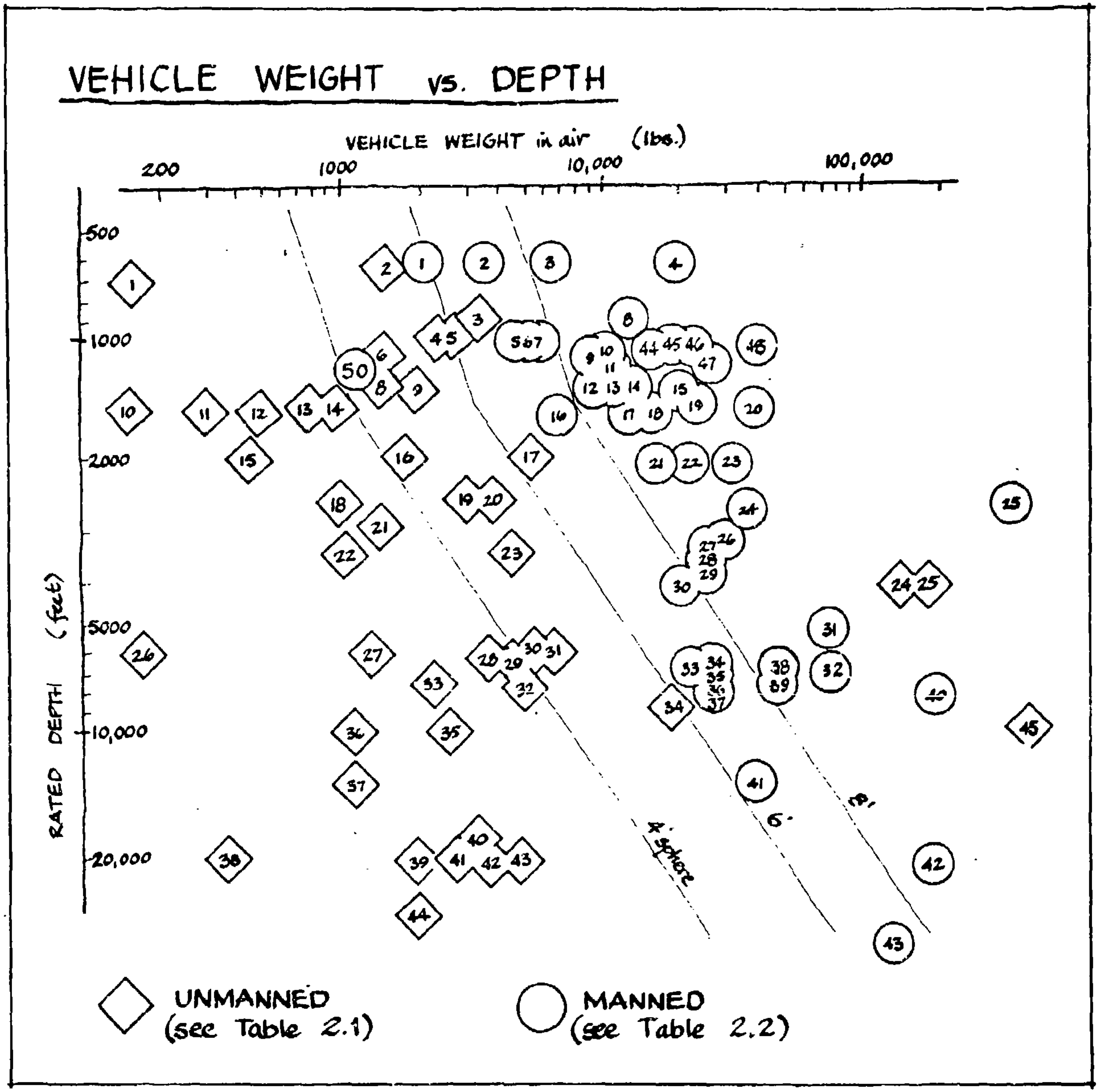


FIGURE 2.1 VEHICLE WEIGHT VS. DEPTH. Manned submersibles must necessarily be more massive (and more costly) the deeper they go because of the necessity of providing one atmosphere and minimum space for pilot and observer. Theoretical limits are shown for 4-, 6- and 8-foot spheres. These are based on steel (σ = 80,000 psi, E = 30 x 10^6 psi), a ratio of 1.5 for collapse depth to operating depth and a ratio of 3 for vehicle weight to pressure vessel weight (Evans, 1969).

The weight (and cost) of an unmanned submersible is less dependent on depth and more dependent on the tasks it is designed for. For example, vehicles for sensing (20, 27, 32) are light compared to those for pipe-line repair (24, 25) or mining (45).

Though cost data are mostly not available we venture that weight is probably the best single predictor of vehicle cost.

2.2 Future Undersea Vehicles

Figure 2.2 portrays an important three-way classification in undersea work vehicles in terms of whether vehicles are manned or unmanned, tethered or untethered.

In the previous chapter we commented that, as work vehicles (i.e., for inspection and manipulation, neglecting personnel rescue or tranfer from undersea habitats), there remain only minor advantages to manned submersibles if the communication link and control systems function well. The advantages are rapidly being counterbalanced by disadvantages. The advantages are stereopsis of human vision at close range, high resolution combined with a wide field of view, and the ability of the human operator naturally to change his direction of view while maintaining a sense of where he and various environmental objects are located relative to one another. But these advantages may be counterbalanced by the costs of the man, the pressure vessel and the required life support equipment.

Experiments in video stereopsis suggest that such techniques are gradually becoming practical. Resolution can be obtained by remotely controlled zoom lenses. As for proprioception (keeping track of the configuration of the remote mechanical arm) this is known to be an important drawback of present teleoperation techniques; but there are promising possibilities for "teleproprioception" using head mounted CRTs, fiber optics, and the like, and using replica controllers and local models. (This is discussed further below.) Thus, as the prerequisites of communication and control are fulfilled, the functional advantages of the manned submersible are disappearing, while the cost disadvantages remain.

One further motivation for building so many manned submersibles, as compared to emphasizing unmanned teleoperation, should be mentioned. It is the same

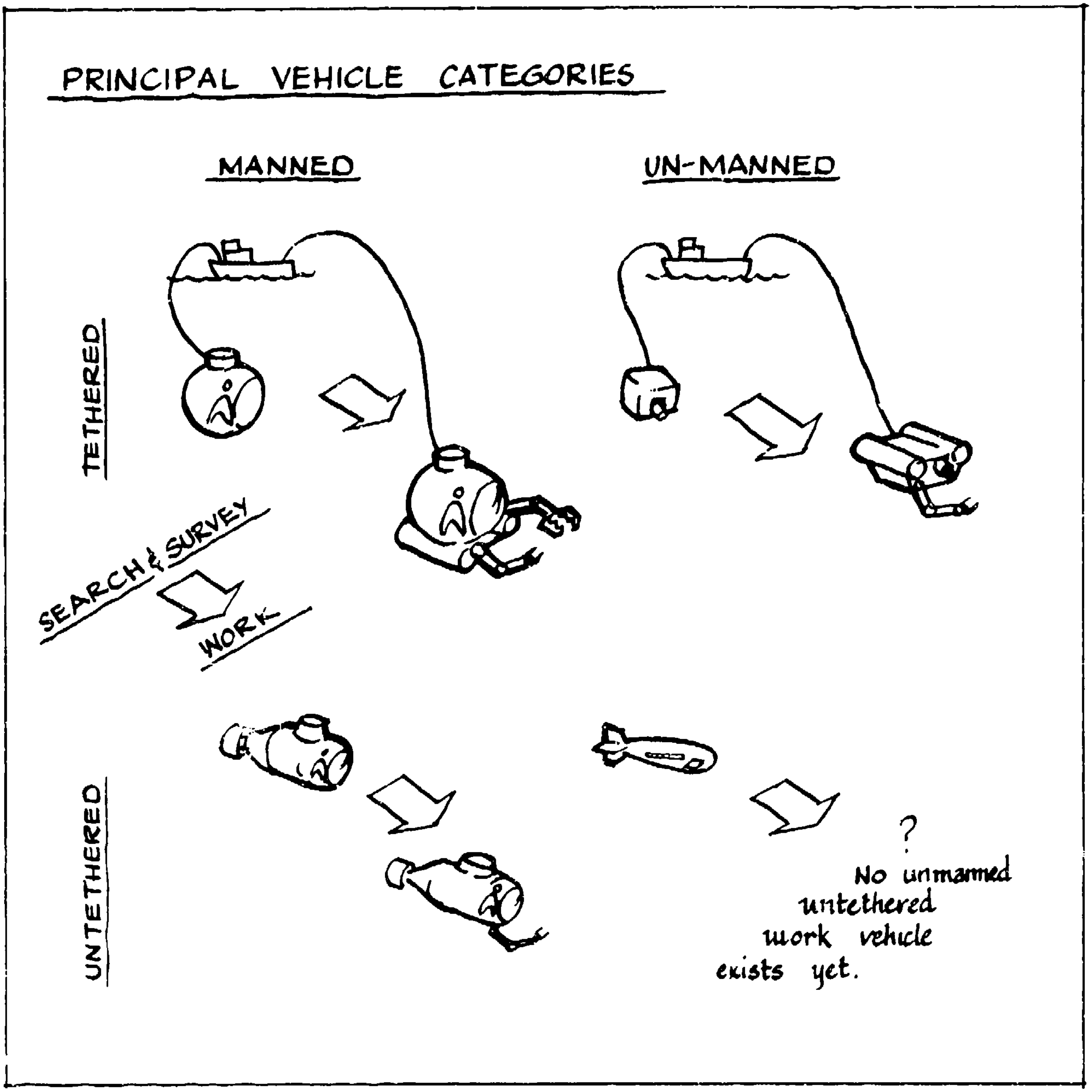


FIGURE 2.2 VEHICLE CATEGORIES for general purpose submersibles can be used for describing needed future developments.

As operations approach greater depth the increased cost and safety requirements suggest UNMANNED vehicles. Problems of reduced mobility due to tether drag, tangle and snare suggest UNTETHERED vehicles. Most undersea operations are incomplete without some kind of manipulation or WORK, for example search and recover, select and sample, inspect and repair.

The few untethered unmanned vehicles in existence are only search and survey vehicles. Significant problems of limited communication must be solved to provide either better control from the surface (teleoperation) or automatic control (robotics) or a combination (supervisory control).

motivating factor we have observed in the space program, namely the natural desire of the human being to achieve and experience actual presence in new places. As with space, we expect that in time teleoperation will have both the economic and the functional advantage for undersea operations below a few hundred feet in depth.

Figure 2.3 portrays a two-way classification of unmanned work-vehicles (the two right-most configurations in the previous figure). The vertical differentiation of Figure 2.2 (tether vs. no-tether) breaks down further in Figure 2.3 into tether (which can support communications and power) vs. sonic communications(with the wave pattern indicating sound messages can go both ways) vs. no communications at all (a purely "robotic" vehicle). Figure 2.3 differentiates horizontally on the basis of whether or not there is an intermediary vehicle or structure - a "garage" we call it - which can serve several functions:

1. it can serve as a terminus for a tether and avoid loading the teleoperator with mechanical forces due to surface waves on the support ship and to ocean currents integrated over the whole tether;
2. it can store energy and allow a battery-powered teleoperator to return to get powered-up;
3. it can serve as a communications way-station and permit higher bandwidth sonic communication (because of short distance) with the teleoperator at relatively low power.

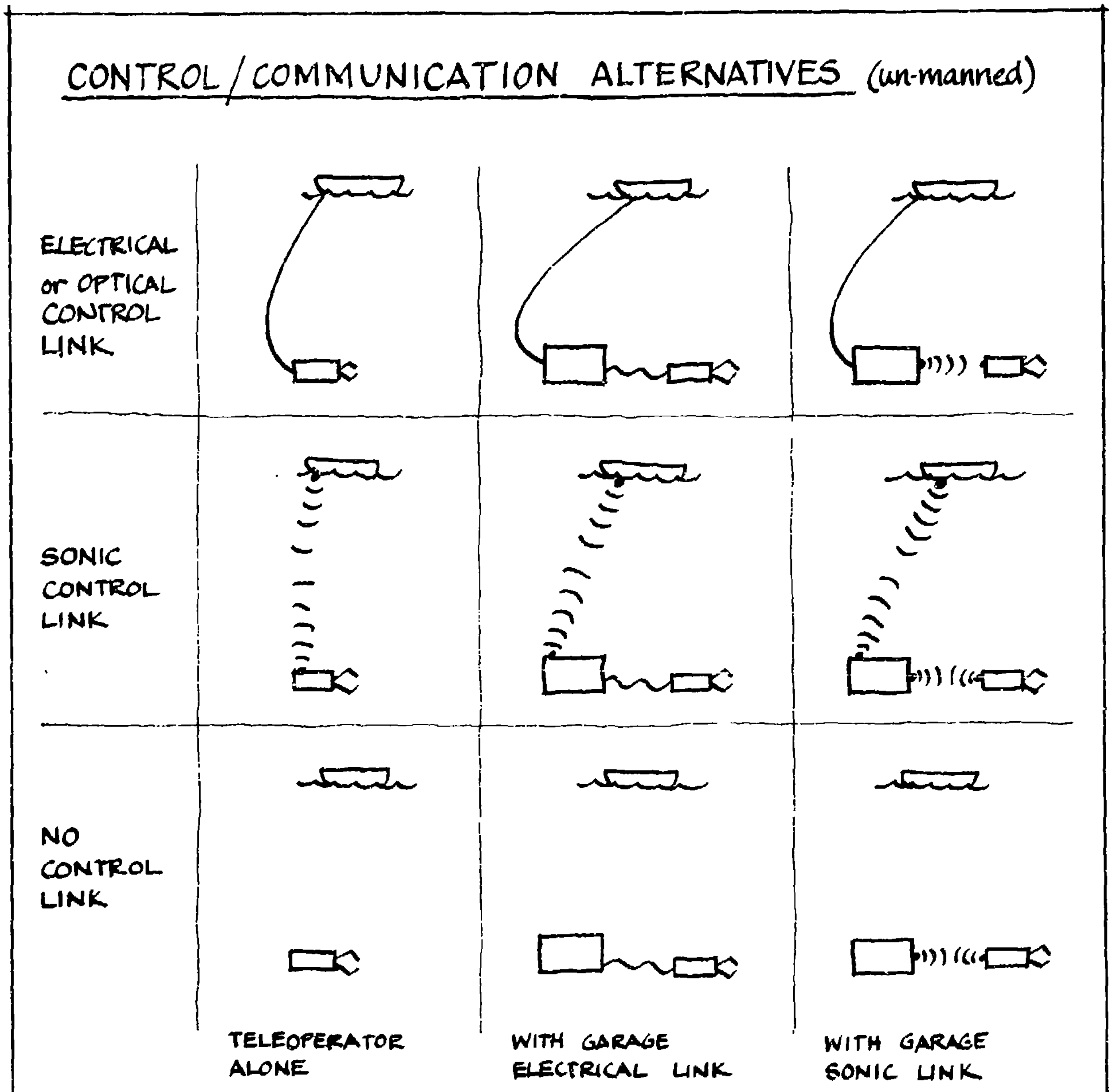


FIGURE 2.3 COMMUNICATION ALTERNATIVES for unmanned vehicles will be important in determining the trade-off between human and computer control. The particular configuration will, of course, depend on task to be accomplished, operating depth, size, speed, power source, duration, etc. The above matrix classifies alternative forms of communication: 1) with the surface ship (if any); 2) with an intermediary "garage" (if any).

3. UNDERSEA TASKS

3.1 Classification of Tasks

Teleoperators are used for inspection and manipulation of the undersea environment. Inspection can be of anything that a sensor can sense and for which some mobility is necessary for bringing the sensor to the appropriate location and searching. In addition to the obvious need to see and locate (e.g., through sonar) natural and man-made objects many other environmental properties are of interest. Talkington (1976) presents an interesting list of such properties which suggests the ocean depths at which such sensing is appropriate (Table 3.1).

Perhaps it is possible to be somewhat more specific with respect to manipulation tasks. Drenning (undat.) outlines what can be done with manipulators in Table 3.2.

All of these tasks must be accomplished in an environment that at times can be extremely severe: rough seas (an air water interface capable of demolishing equipment which is not rugged), corrosive salt water, ocean currents of up to several knots which tug on any tether, gale winds blowing on a surface vessel, turbid water which is practically opaque to light, and a rocky and uneven bottom.

3.2 Task-Tool Matching

The design and control of teleoperators for undersea tasks obviously depends upon what those tasks are. This is true even though teleoperators are claimed to be general purpose inspection or manipulation devices. The point is that any one teleoperator is relatively general purpose within some necessarily limited range of capabilities. A teleoperator suited for heavy construction is not the best one for repairing a watch.

As with any task and any tool or instrument for accomplishing that task,

TABLE 3.1 OCEAN EXPLORATION AND SURVEY PARAMETERS. (Talkington, 1976)

Parameter	Air-Sea Interface (10 to -10 m)	Upper Water Column (-10 m to -500 m)	Lower Water Column (-500 m and deeper)	Bottom	Subbottom
1 Ice	X				
2 Sea-swell-surf	X				
3 Surface meteorology	X				
4 Surge	X				
5 Tides	X				
6 Currents	X	X	X		
7 Hydrodynamic forces	X	X	X		
8 Noise	X	X	X		
9 Salinity	X	X	X		
10 Temperature	X	X	X		
11 Turbidity	X	X	X		
12 Biomass	X	X	X	X	
13 Nutrients	X	X	X	X	
14 Oxygen	X	X	X	X	
15 Pollutants	X	X	X	X	
16 Electrical		X	X	X	
17 Bathymetry				X	
18 Geomorphology				X	
19 Rheology				X	
20 Engineering properties				X	X
21 Geochemistry				X	X
22 Geology				X	X
23 Geothermal				X	X
24 Physical properties				X	X
25 Radiometric				X	X
26 Gravity					X
27 Magnetics					X
28 Seismic					X

- Salvage
  - Detach cables restraining objects to be salvaged
  - Clear debris away from objects to be salvaged
  - Prepare object for lifting by attaching cables
  - Position objects for salvage
  - Separate large objects
  - Excavate bottom sediment
- Undersea Rescue
  - Aid in freeing entrapped submersibles
  - Aid in mating of rescue submersible to submarine
- Service Habitats
  - Aid in heavy work operations
  - Aid in replenishment of supplies
  - Aid in placement and recovery of habitats
- Offshore Oil/Gas Production Facilities Task
  - Assist during drill string landing
  - Prepare drill sites by removing debris
  - Replace blowout preventer rams
  - Make pipe connections
  - Replace and patch pipes
  - Recover objects dropped from drill platform
  - Inspect oil lines using hand held acoustical devices
  - Remove marine growth
- Others
  - Place and retrieve acoustic markers
  - Place explosive devices
  - Clear and remove debris
  - Collect marine samples
  - Position transponders
  - Remove and replace defective equipment
  - Take bottom core samples
  - Collect mineral laden nodules

TABLE 3.2 TYPES OF TASKS A MANIPULATOR CAN PERFORM ON UNDERWATER MISSIONS. (Drenning, undated)

teleoperators and undersea tasks must be matched in terms of a number of physical variables if they are to co-function. The classes of these variables are shown in Figure 3.1. The match requires that the range of each variable characteristic of the task lie within the operating range of the teleoperator.

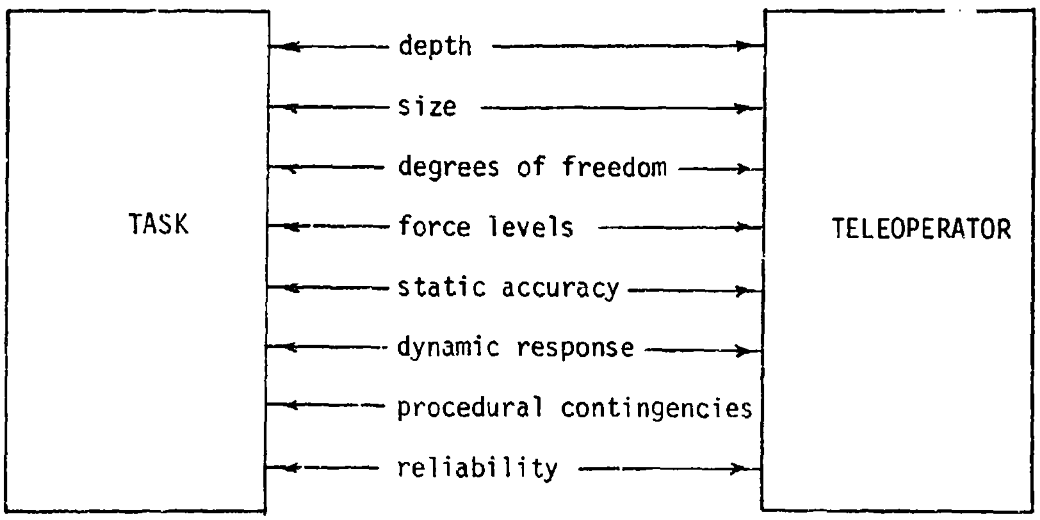


FIGURE 3.1 CLASSES OF VARIABLES WITH RESPECT TO WHICH TASK AND TELEOPERATOR MUST BE MATCHED.

3.3 Problems of Specifying the Attributes of Undersea Tasks

Specification of the attributes, the characteristic variables, of real undersea tasks can never be precise. This is for two reasons:

1. Different operational needs, plus different equipments by different manufacturers, plus natural technological evolution of devices and procedures, make the tasks a continuously evolving process.

2. Those who have analyzed undersea tasks have used different approaches. The choice of task analysis technique is arbitrary.

Our approach to task analysis was to visit and talk with a number of government and private agencies - undersea operating companies, Naval laboratories, etc., - and review the diverse literature in the area. From this we have discovered that there is some apparent consensus, though the approaches to analysis are varied. We give examples below.

3.4 Methods of Specifying and Analyzing Undersea Tasks

At a "mission" level, specification of the task is done by maps and cross-sectional diagrams of the location, terrain, types of structures or cables to work with or around, bottom conditions (i.e., soft mud, boulders, etc.), water turbidity on the bottom, prevailing current velocities, surface conditions (ice, depending on location; waves, depending on season and weather).

A typical next level of task analysis is to break some "overall task" or "mission" into smaller elements which are common to all tasks. This common set of subtasks is comparable to the "therblig" set developed by Lilian Gilbreth (and named after her, only spelled backwards) and by other industrial engineers to characterize common task elements of human workers on the production line.

Such analysis can be done in several different ways. One is to indicate whether (and/or how often, or to what degree) certain subtasks occur within each larger task or mission. Figure 3.2, an analysis by Bien and McDonough (1971) is an example of this, for the particular case of human divers performing Naval undersea missions. It cross plots "performance requirements" with type of manual task.

A related form of such analysis is a time line, as illustrated in Figure 3.3, (same authors). By scaling the time axis as a percentage of total time, one can make quick judgements about where most of the time is spent. Also, one can

Undersea Missions and Operations \ Generalized Task Spectrum	Class I: Search/Locate	Class II: Observe	Class II: Survey	Class II: Measure	Class III: Pickup	Class III: Transport	Class III: Place	Class IV: Attach {Drill, Bolt, Rivet, Connect/hookup, Clamp}	Class IV: Detach {Drill, Burn, Saw, Hammer, Chip, Scrape, Wipe}	Class IV: Apply (Fill) {Hose, Paint}	Class IV: Excavate {Core, Dredge, Trench, Tunnel}
Surveillance											
Landing beach area		X	X		X	X	X				
Enemy harbor		X	X		X	X	X				
U.S. harbor protection		X	X		X	X	X				
Inshore USW		X	X		X	X	X				
USW all ranges & depths		X	X		X	X	X				
Reconnaissance											
Beach area	X		X	X	X	X	X				
Enemy harbor	X		X	X	X	X	X				
Mining environment	X		X	X	X	X	X				
Mining											
Mine hunting and countermeasures	X		X	X		X	X				
Mine plants						X	X				
Disarm mine								X	X		X
Interrogate mine fields	X	X	X								
Navigation Surveys											
Recovery											
Small object	X		X		X	X					
• Torpedoes	X		X		X	X					
• Nuclear weapons	X		X		X	X					
• Space hardware	X		X		X	X					
Large object	X		X	X	X	X	X	X	X	X	X
Facility Installations											
Sonar array (align & repair)			X	X	X	X	X	X	X	X	
Bottom mounted UIM			X	X	X	X	X	X	X	X	X
Navigation markers			X	X	X	X	X				
Cable laying & inspection			X	X	X	X	X	X			
General construction			X	X	X	X	X	X	X	X	X
Salvage											
Ships	X	X	X	X	X	X	X	X	X	X	X
Aircraft	X	X	X	X	X	X	X	X	X	X	X
Repairs											
In port (wet dock)								X	X	X	
Underway								X	X	X	
Support											
Oceanographic data					X	X	X	X	X	X	X
Sub rescue personnel	X	X	X			X	X	X	X	X	X
Underwater logistics		X			X	X	X	X	X		
Habitat Development											

FIGURE 3.2 NAVAL UNDERSEA MISSIONS, OPERATIONS, AND ASSOCIATED TASKS. Shading indicates that task occurs in broad mission area, X indicates that task occurs in narrow mission catgegory. (Bien and McDonough, 1971)

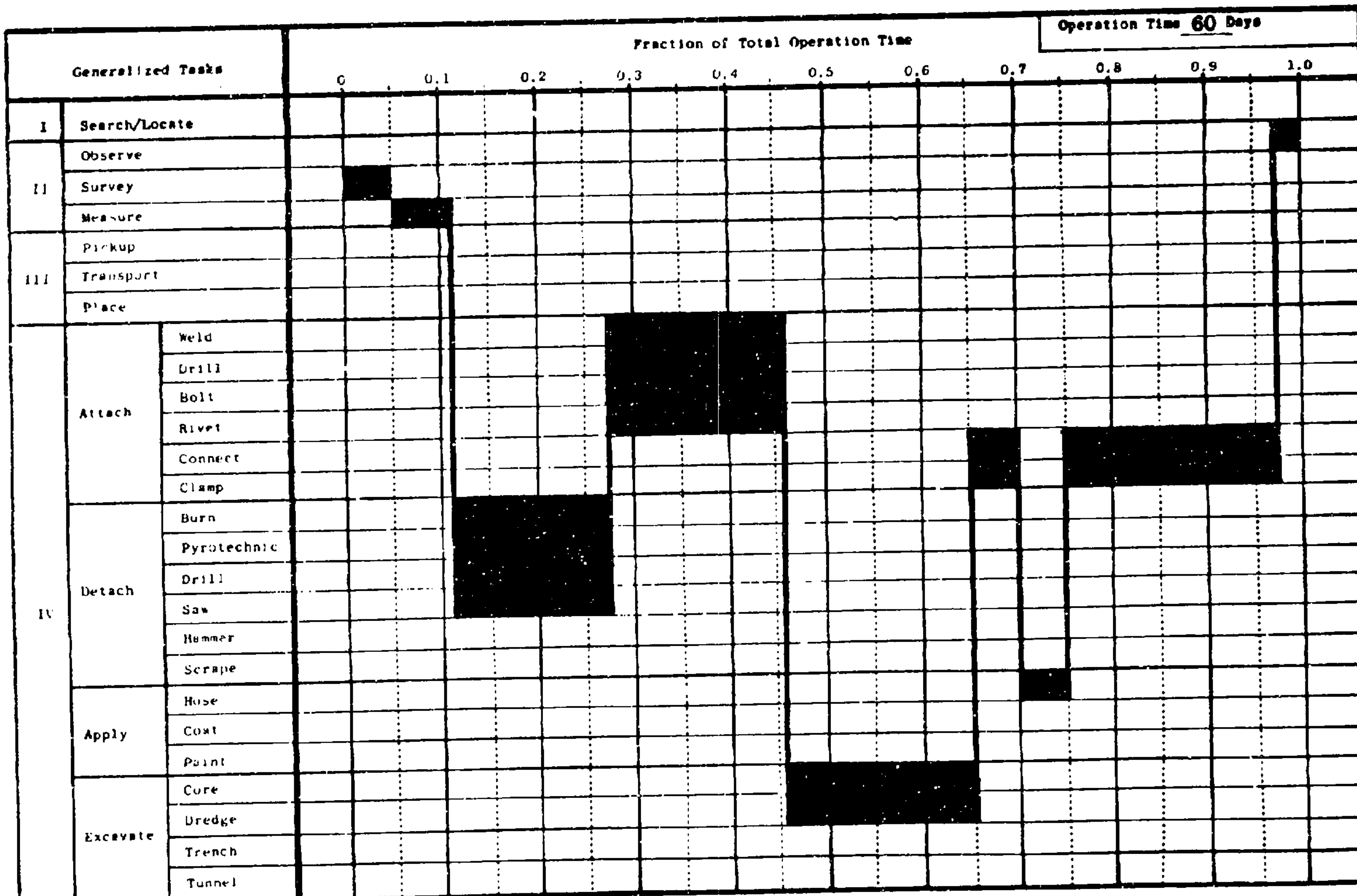


FIGURE 3.3 TASK-TIME DISTRIBUTION FOR SHIP SALVAGE OPERATION.
Shading indicates task activity for associated period of task.
(Bien and McDonough, 1971)

see what subtask elements tend to go together.

By integrating over all subtask elements and over a variety of tasks or missions, one can produce a pie-chart or comparable representation showing the fraction of total tasks and/or fraction of total task time (which are, of course, different!) for undersea tasks.

Figures 3.4 and 3.5, replots of fraction-of-total-task data from Ocean Systems, Inc. (1977) show such data. Figure 3.4 relates force and accuracy. The important message of Figure 3.4 is that 80% of all tasks require neither high torque/force nor fine orientation movements. The important message of Figure 3.5 is that 31% of all underseas tasks are visual inspection tasks, requiring no manipulator at all, while 22% (according to this analysis) are involved with removing and installing flexible wires and slings. It is important to keep in mind that in such task analyses the quantitative ranges of categories (e.g., on force) are arbitrary and the assignment of cases to such categories surely involves a great deal of subjective judgement. Nevertheless, such analyses provide useful, if coarse, information to the designer or operational decision-maker.

Figure 3.6 (from Pesch, Klepser et al., 1970) illustrates the complementary plot, fraction of total time for different work segments, in this case for the task of recovering five 50 lb. lead samples from the ocean floor.

In our own laboratory Schneider (1977) performed a task analysis in which he broke what might be considered mission subtasks (lefthand column of Table 3.3) into two lists: general work tasks and tasks specialized to the oil industry. Then he made a further breakdown according to: forces (how much indicated in parentheses) in rotation or translation, whether they are constant or impact forces; placements or positioned movements, qualified by what kind; what mode of sensory feedback to the human operator is salient; and finally some statistical attributes of the situation geometry and some factors relating to whether two arms and/or special tools are needed. The numbers 1, 2, 3 represent the sequencing of steps within a task, the letters

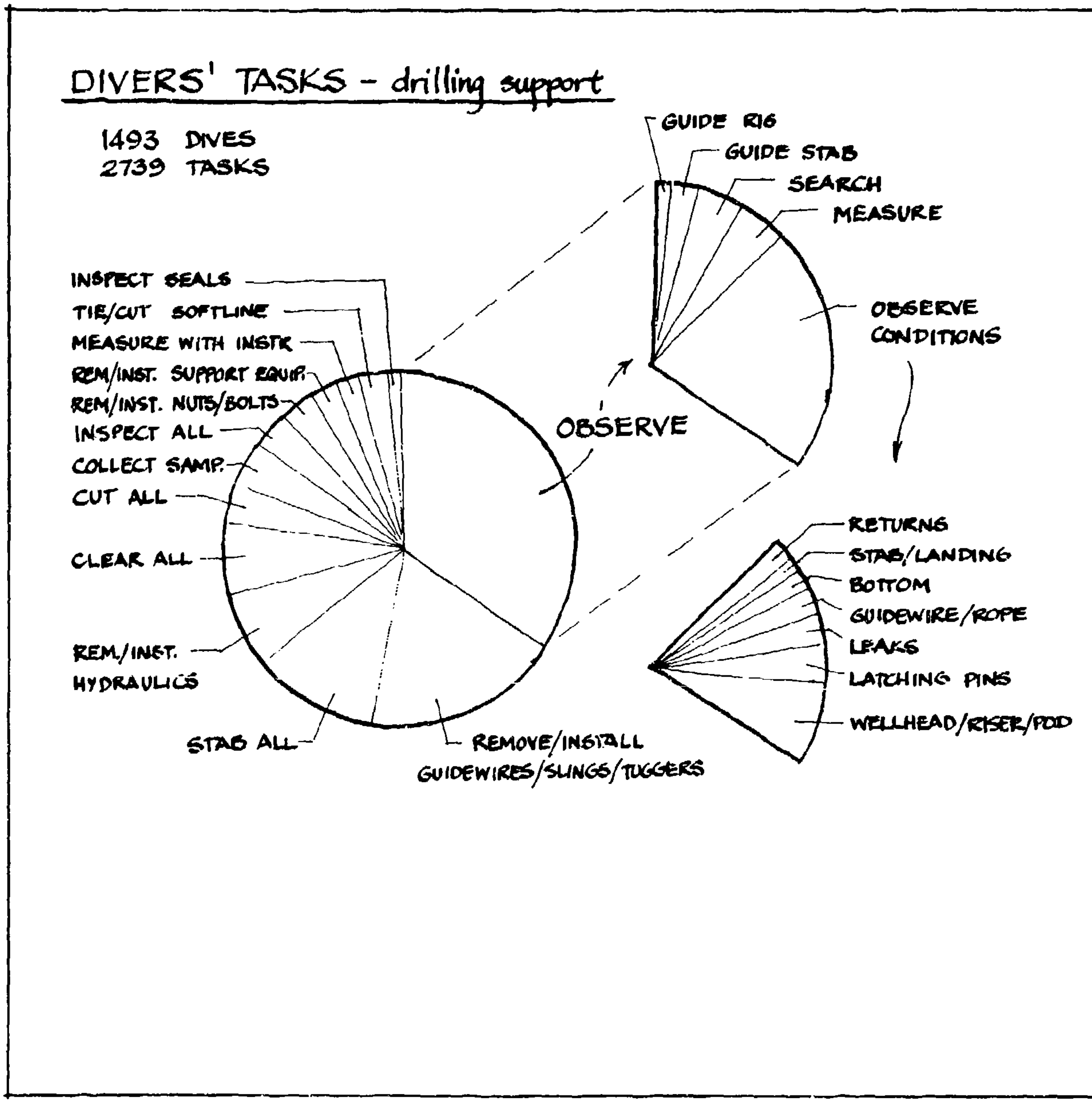


FIGURE 3.4 DIVERS' TASKS. Ocean Systems, Inc., (1977), a diving service company, compiled statistics on what tasks their divers performed on 1493 separate dives in support of undersea drilling operations. Observation accounted for only 31% of the tasks; all the rest involved some form of manipulation. The various actions are categorized in Figure 3.5 according to force and dexterity required.

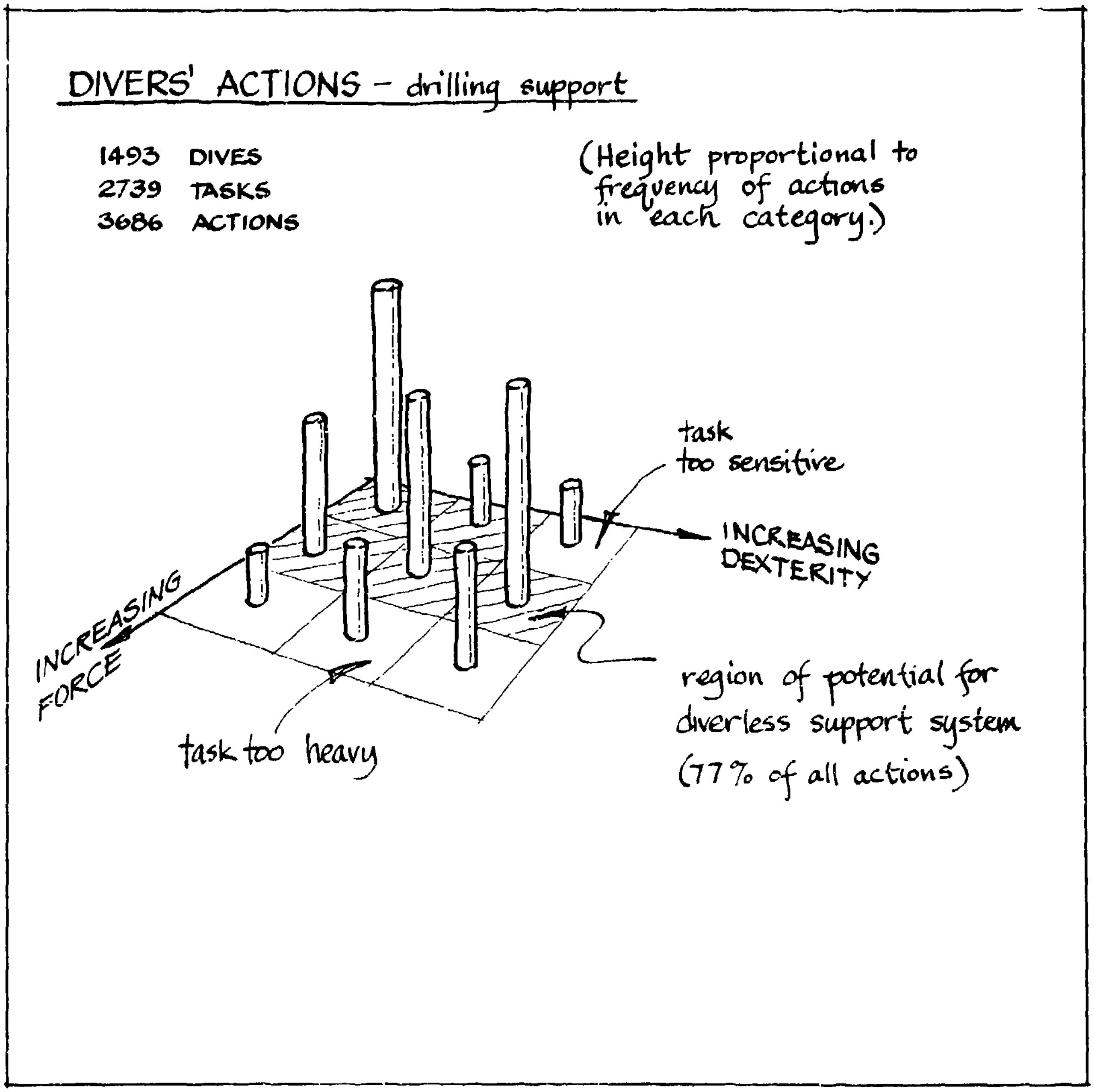


FIGURE 3.5 DIVERS' ACTIONS were classified by Ocean Systems, Inc., (1977) into nine classes depending on the force and dexterity required. For example, the heavy force was any action requiring a pull of over 50 lbs. The three classes of manipulative dexterity were gross positioning such as swimming and dropping (37%), accurate positioning relative to a fixed point such as with a crane (30%), and accurate positioning and orientation at a fixed point such as the diver's wrist provides (33%).

An unmanned "diverless support system" might not be able to do the highest-dexterity-lowest-force actions or any of the high-force actions but that leaves 77% of all tasks. "In combination with special tools, manipulators could perform almost all divers' tasks."

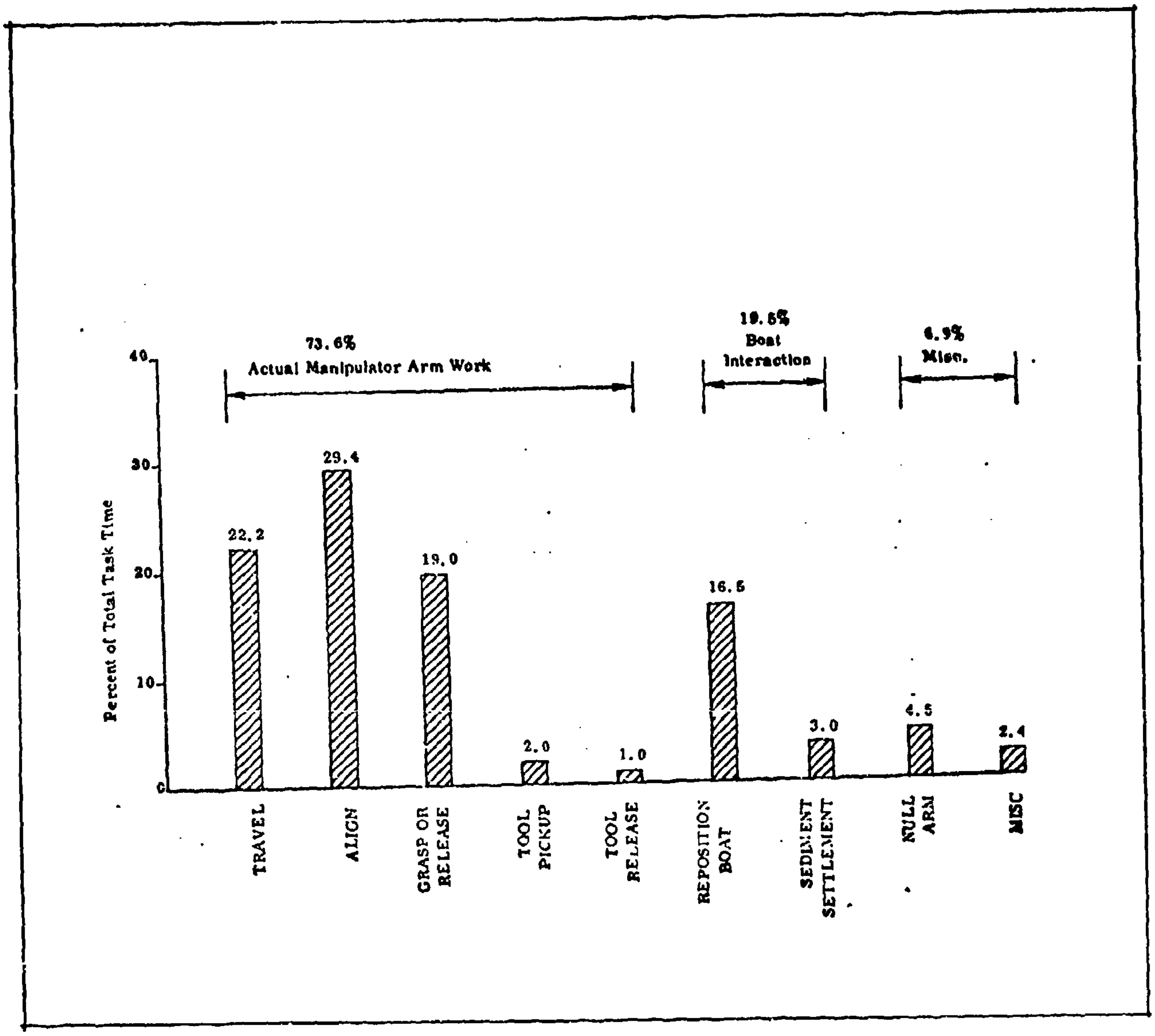


FIGURE 3.6 FRACTION OF TOTAL TASK COMPLETION TIME FOR DIFFERENT WORK SEGMENTS. Task was recovering 50 lb. lead sample from ocean floor. (Pesch et. al., 1970)

TASKS	FORCES		MOD		PLACEMENTS				MOD		FEEDBACK				GEOMETRY		TWO ARMS			
	rotate-small radius (ft.-lbs.)	push/pull (lbs)	constant force	impact force	orient (θ_x, θ_y, θ_z)	align (θ_x, θ_y, θ_z, X, Y, Z)	complex motion	move along a curved surface	medium precision	high precision	visual	special sensor	tactile	gross force	totally unpredictable	high possibility of obstruction	two arms semi-constrained	one end against force	two free ends in relation to each other	special tool required
General work tasks:																				
assessing damage								1			1 m	1 m		1 L	1					x
bolting/unbolting	2 (200θ)					1					1 m		1 C	2 m						x
burning		2 (5)	2		1						1,2 m,C					1				x
connect push/turn hose	3 (10)	2 (15)				1					1 m			2 L						
cutting small pipes		2 (10)				1		2	1		1,2 L,m			2 m						x
cutting wire and cable		2 (10)			1						1 L			2 L						x
digging		2 (50)						2			1 L			2 m						
drilling	2 (0.6θ)	3 (25)				1				1	1 m			3 L						x
latching		1 (50)						1			1 L			1 m	1					
lift one object to search		2 (50)						2			1,2 m,C			2 C		2		2		
pulling things apart		1 (50)		1					1		1 m			1 m						
reaching into confined space						1	1				1 C			2 C	1					
recovering lost equipment		2 (50)				2				2	1 C					1				
threading cables					1		1			1	1 C		1 C			1				
threading line through eye					1				1		1 C									
tying knots							1			1	1 C		1 C		1				1	
tying shackles						1	1			1	1 C		1 C							
tapping holes	2 (1.0θ)		2			1				1	1 m		2 C							x
untangling cables						1			1		1 C				1				1	
water jetting					1			2		1	1,2 m,m				1					x
welding		2 (5)	2		1			2 L	1	2	1,2 m,C					1,2				x
wire brushing	2 θ	1,2 (25)			1			2			1,2 L,m			2 m						x
Oil industry/research tasks:																				
attach lifting device								2			1,2 C,m	1 C				2				
operate mechanical override		1 (10)						1			1 L			1 L						
replace offset beacons	3 (20θ)	1 (100)				1,2					1,2 m,m		2 C	3 m	1					x
replace riser angle indicator	3 (100θ)	1 (30)				1,2					1,2 m,m		2 C	3 m	1					x
reconnect lost riser		2 (max)			2						1,2 m,m									
reconnect lost guideline	3 (200θ)				1	2				2	1,2 m,m			3 m						
provide tool guidance		2 (max)			2						1,2 m,m									
disconnect guide arm	2 (200θ)	3 (5)			3	1			3		1 m		1 C	2 m						
attach listening device					1			1			1 L			1 m						
replace anodes	2 (200θ)	1 (50)			1	2					1 m		1 C	2 m						
untangle cable					1		1				1 C								1	
secure shaped charge		1						2			1 m									
release buoy from pipe		1 (20)									1 m			1 m					1	x
handle underwater explosives	2 (0.6θ)	2 (25)				1				1	1 m			3 L						x
run lines and slings					1		3	2 L		1	1,2 m,m								3	x
remove concrete from pipe		1 (50)		1							1 m			1 C						x
insert "O" rings	3 (200θ)					1,2					1,2 C,m			2 m			2			
place sleeves around pipe		1 (50)				1					1 m			1 C		1				
orient swivel joint		2 (max)		2		2					1,2 m,m									
water jetting					1			1			1 L									
measure depth of cover		1 (m)			1						1 m			1 m						x
coring	1 (1.6θ)	2 (30)			1						1 L			2 m						x
large rock sampling		1,2 (50)		1	2	3					1 L			2 m			3			

TABLE 3.3 ANALYSIS OF REPRESENTATIVE UNDERSEA TASKS. Numbers 1, 2, 3 represent order of subtasks within a task. Letters m and L indicate "medium" or "long" update periods between visual samples, as compared to continuous update, C. Numbers in parentheses have dimensions noted in column heading. (Schneider, 1977)

M and L indicate that "medium" or "long" (occasional) update periods between visual samples will do, as compared to continuous update, C.

Given Schneider's results, it is evident that translational force requirements seldom exceed 50 lbs., that vision contributes to every task, that gross force (as might be felt by a person in the muscles and tendons, and is built into force-reflecting master-slave manipulators) is next most important. Special tools seem to be needed for about half the tasks.

Figure 3.7 characterizes task requirements of special end-effector tools, which typically are attached on to the end of the arm in place of the grippers and driven hydraulically. Naturally, these special tools are needed because the grippers will not perform the required actions. Figure 3.7 describes the end-effector movement requirements by "adverbs" (different columns) indicating how or what kind of action (row) is necessary.

A quite general way to characterize a particular task is in terms of a flow chart, such as is used to characterize a computer program (which, of course, is a description of an information processing task). Figure 3.8 gives an example of such a flow chart applied to a hypothetical oceanographic sample collection task. Rectangles represent actions, diamonds represent decisions. Such diagrams allow as detailed a specification of a task as the analyst has patience for. This type of analysis specifies where measurements must be made, where controlled actions must be taken, and generally deals with the kind of information necessary either for programming a computer or for teaching an operator to do a task.

A close cousin to the flow chart is the PERT chart, or time precedence diagram. Figure 3.9 illustrates the idea using a similar hypothetical task. The special significance of this diagram for task analysis is that it tells what must be done before what else, or when it doesn't matter which goes first. It is a useful tool for planning a mission and predicting how long it will take.

When there is a relatively common set of elements, one may do a frequency count on transitions between task elements, and summarize the analysis by a transition diagram, Figure 3.10. The elements between which the frequency is

Salvage-System Requirement	Linear Steady	Linear Reciprocating	Rotary Steady	Rotary Impact	Remarks
Cutting					
Hacksaw	X	(X) ←	→ (X)		
Hole saw 1-3/4 to 4 inch	X		X		
Saber saw	X	(X) ←	→ (X)		Hole must be drilled or punched to start
Shear	X				
Snips	X				
Torch	X		X		Torch moved in straight or circular path
Explosion rope					Linear motion for placing
Machining					
Milling hole 4 to 24 inch	X		X		
Drilling hole 1/2 inch Ø to 1-1/2 inch Ø	X		X		
Attaching					
Bolt	X		X	X	A hole must be drilled and tapped for bolt
Velocity stud	X				Locating operation required and triggering
Rivet	X	(X)			Drill hole first
Net	X				Linear motions for placing
Hook	X				Ditto
Strap	X				
Weld	X		X		
Cleaning					
Brush		X	X		
Grind		X	X		
Jet		X			
Chip		X			
Miscellaneous					
Punch	X				
Unscrew			X	X	
Pry	X				
Jack					

FIGURE 3.7 END EFFECTOR TOOL MOTIONS FOR SALVAGE TASKS. (Battelle, 1976)

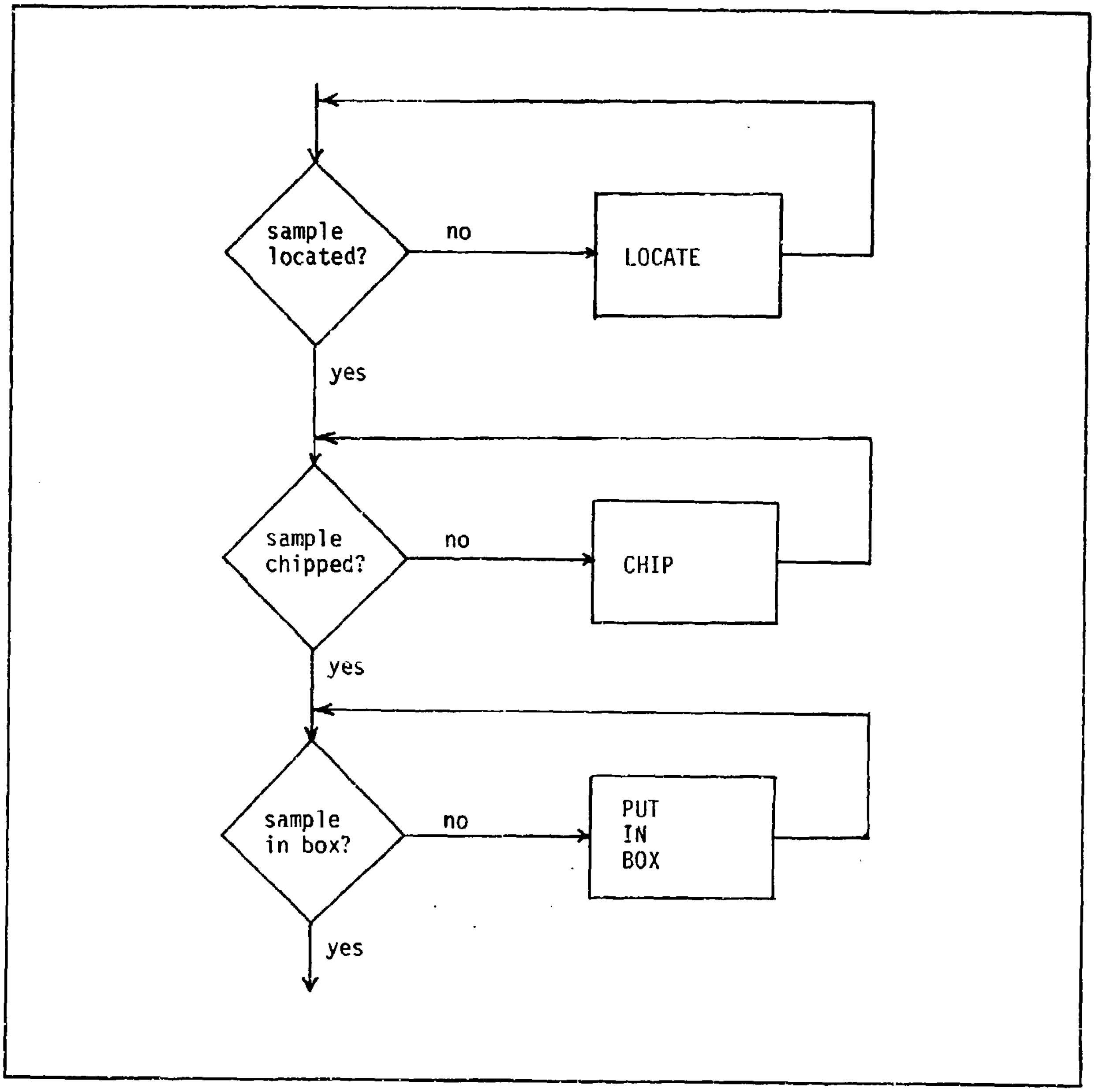


FIGURE 3.8 FLOW DIAGRAM OF OPERATIONS IN SAMPLE COLLECTION TASK. Rectangles represent actions, diamonds represent decisions (based on measurements).

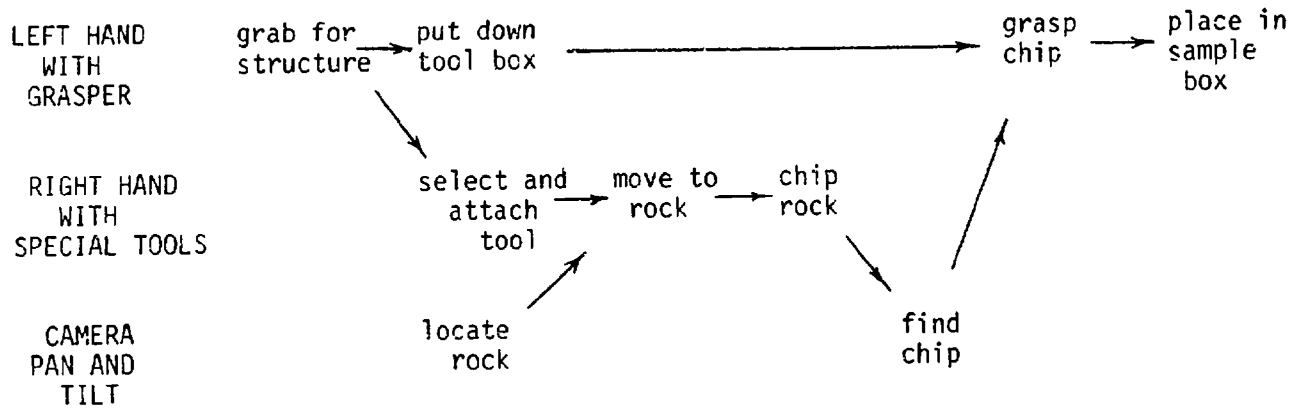


FIGURE 3.9 PERT CHART (or TIME-PRECEDENCE DIAGRAM). Arrows represent time precedence, i.e., what steps must be completed before what other steps are begun.

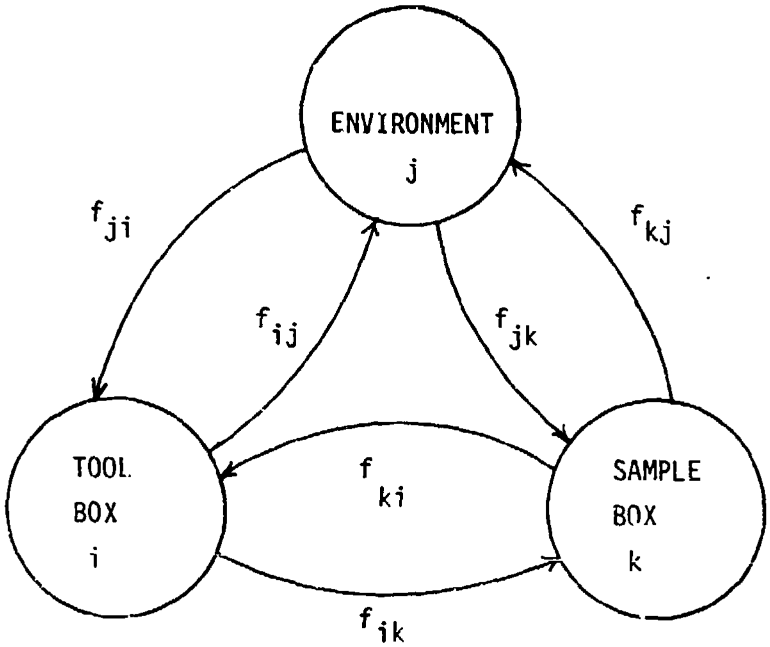


FIGURE 3.10 FREQUENCY TRANSITION DIAGRAM. Circles represent locations. Lines represent transitions between states, with state transition frequencies indicated.

highest should be moved in closest proximity or most facilitated to minimize time and errors.

There are many other ways to analyze undersea tasks , but the examples cited above provide a cross-section.

3.5 Tasks in the Laboratory Environment vs. Tasks in the Real World

In designing, building and testing teleoperators, and in trying to understand the nature of actual undersea tasks, it is useful to devise experimentally controlled laboratory tasks. Essentially , with the laboratory task it is not the accomplishment of the task per se which is important, but the manner of doing the task - either as a demonstration that a particular teleoperator can do a particular task, or as a measure of how quickly a fixed-accuracy task can be done, how accurately a fixed-time (or open ended) task can be done, etc.

The laboratory task can be repeated, so that reliability measurements are possible. The laboratory task can be scaled, so that the same basic task can be posed but with different tolerances, or sizes, or orientations, etc.

Laboratory tasks may be differentiated with respect to the following objectives:
(1) The laboratory task may be intended as a simulation of a real task, so that as many elements of realism as possible and practical are brought into the simulation. Alternatively (2), laboratory tasks may be everyday manipulation/ inspection task, which have the attractive attribute that people have some experience with them , understand them, and have some expectations about how they can or should be done. Or (3), laboratory tasks may be "calibration tasks", adjustable in quantifiable ways such that objective numerical scores may easily be obtained. Finally (4), laboratory tasks may be archetypal, selected primarily to "show-off" a particular teleoperator to best advantage.

Figure 3.11, a typical peg-in-hole laboratory task employed by Hill (1977), illustrates a simple means to calibrate both distance, force, and tolerance (between peg and hole). Figure 3.12 illustrates a set of tasks used by Hill which

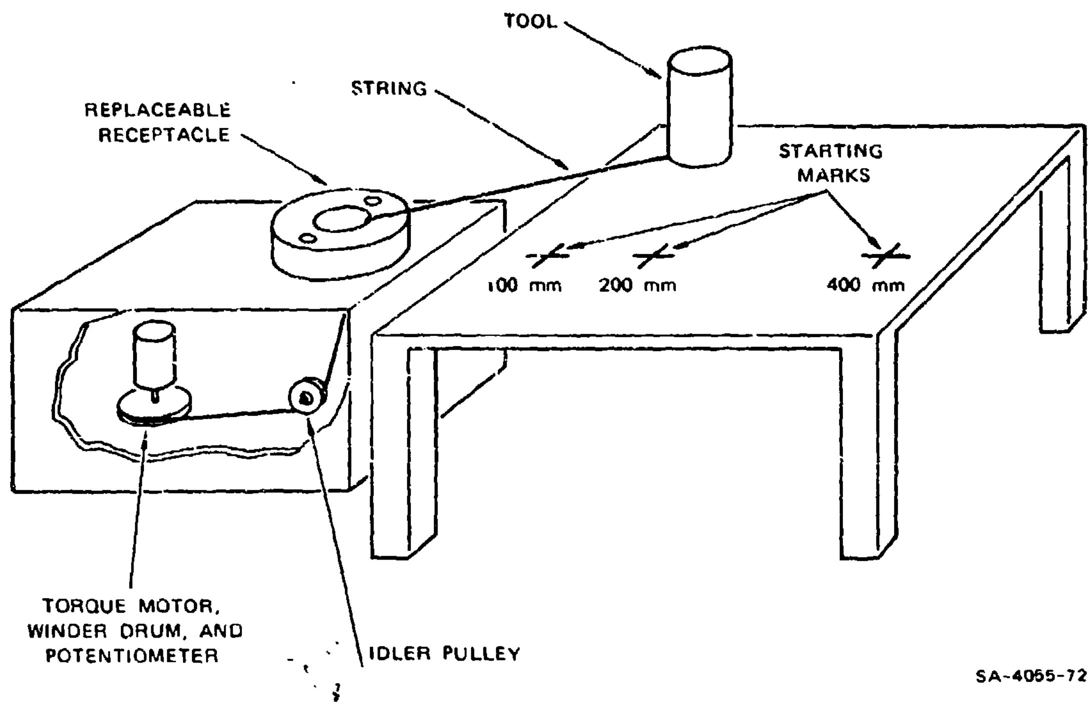


FIGURE 3.11 HILL'S CALIBRATED PEG-IN-HOLE TASK. (Hill, 1977)

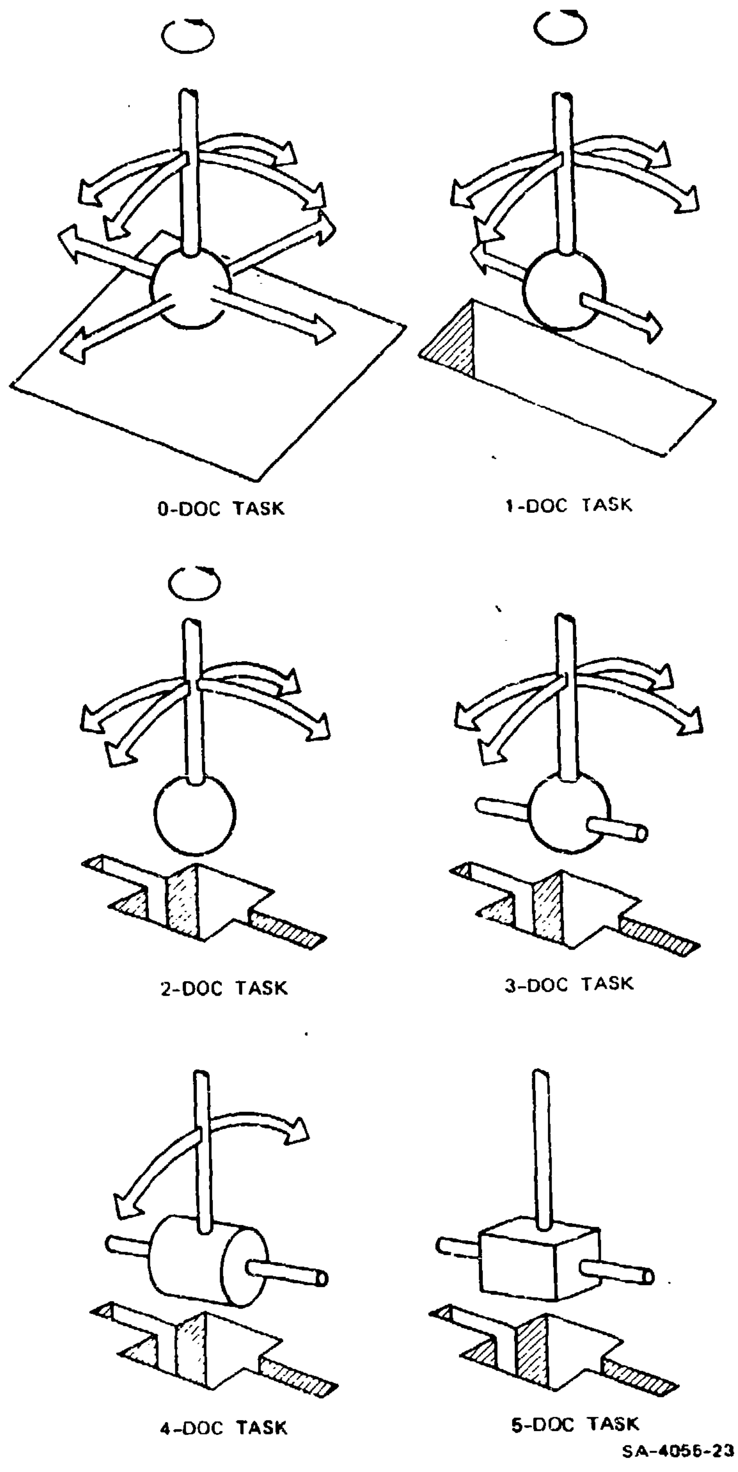


FIGURE 3.12 HILL'S SIX TASKS FOR FITTING TOOLS INTO RECEPTACLES WITH VARYING DEGREES OF CONSTRAINT. (Hill, 1977)

differ from one another in terms of number of degrees of freedom which must be controlled.

The following set of seven task-teleoperator categories is ordered from fully contrived laboratory environment to fully "real world" environment. Between 3 and 4 the shift is made from air to artificial or natural bodies of water.

Laboratory environments:

1. Fully contrived archetypal tasks - explicitly chosen to characterize "the best a given teleoperator can do", i.e., the most accurate, or fast, or complex, etc. task the teleoperator can perform with a trained operator
   - a different set for each teleoperator
2. Calibration tasks - designed to yield objective evaluation measurements
   - standardized battery of tasks accepted within the community of interest
   - task and time constraints well specified and communicated to operator, including time-error tradeoff criteria according to which he will be scored
   - operator usually trained with teleoperator equipment to be used, which may be operational, developmental, or for research
   - test usually repeated over a factorial array of task parameters, criteria constraints or operators
3. "Everyday" manipulation/inspection tasks - usually performed as demonstrations to give observers some intuitive sense of what teleoperator can do by comparison to people. Examples are stacking blocks, putting nuts on bolts, tying knots in ropes, lighting cigarettes, writing name with pencil, etc.
   - same conditions apply as in 2

Underwater Environments

4. Simulated "real undersea tasks" - usually for demonstration
   - time and risk constraints artificially imposed on operator
   - task well known to experimenter, may not be to operator
   - teleoperator equipment may be operational or developmental
   - operator usually chosen to do best possible job
   - may be in water or in air

5. Checkout in protected harbors
   - mild time stress
   - tasks well defined; but turbidity, depth, etc. may be different from operational conditions
   - teleoperator, support equipment and operators carefully selected
   - hazards due to nature removed
6. Sea trials
   - moderate time stress
   - some uncertainties concerning task
   - teleoperator, support equipment and operators selected for test
   - sometimes hazards due to nature, usually none due to enemy
7. Operational mission situations
   - severe time stress
   - uncertainties of what the task is
   - available teleoperator and support equipment not necessarily the most appropriate
   - available operators not necessarily the best trained
   - hazards due to nature and/or enemy

3.6 Formal Specification of a Manipulation Task in N-dimensional State Space

Given all the variables which must be controlled, given the tolerances to which they must be controlled relative to other variables, and given the order in which these control actions must take place, a formal description of a manipulation task can be couched in terms of a "tunnel through state space". By letting each variable be a different orthogonal axis in Cartesian space, including time or higher time-derivatives, we may represent every possible configuration of objects to be manipulated relative to the environment as a single point in this multidimensional space. A connected sequence of such points is a precise specification of how the task was done, or ought to be done, etc., An example from Whitney (1969a) is shown in Figure 3.13.

If each such trajectory point is surrounded by a hypercube which specifies tolerances for each variable at that point in the task, then the connection of all those hypercubes represents a "tunnel" in state space. Such formal repre-

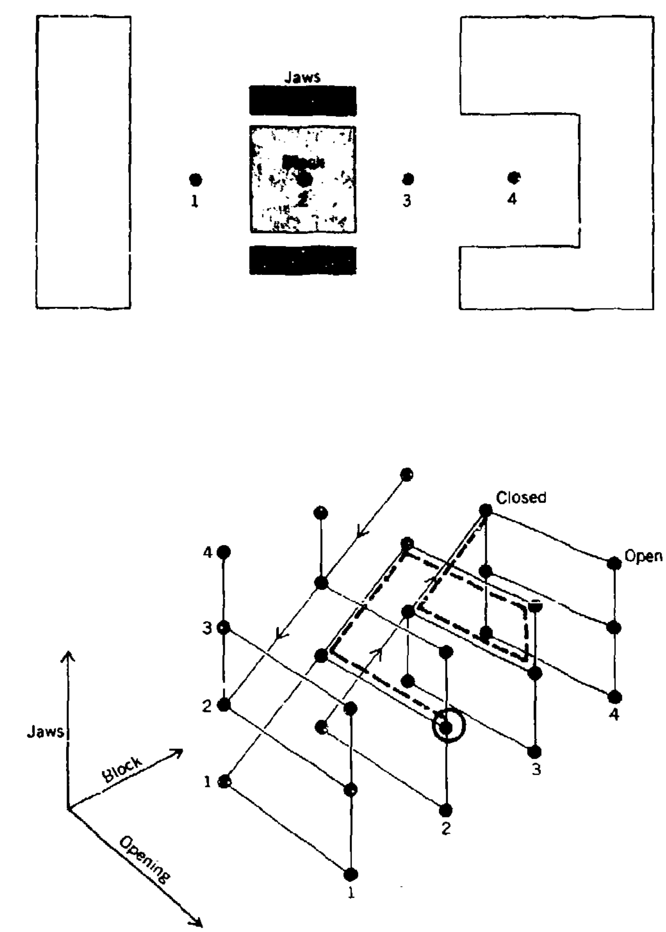


FIGURE 3.13 A SIMPLE TASK AND ITS STATE GRAPH. The upper figure represents a physically two-dimensional task with two moveable objects. Jaws can be opened or closed (one dimension of state space), and/or moved to one of four numbered positions (second dimension of state space). Block can also be moved to one of same four positions (third dimension of state space). Diagonal arrows represent "pushing" from either left or right. The dashed line started at the circle indicates a trajectory required to grasp the block at 2, move it to 3, release it there, get behind it and push it to 4.

sentations of tasks may be useful for theoretical purposes, such as planning of computer programs. The difficulty with the state-space representaton is that a "real" task usually involves sufficiently many dimensions that it is usually too unwieldy for a computer to handle, or a human mind to specify or even comprehend, since the number of states to be stored is the product of the number of variables and the number of states per variable. Optimization requires that all possible sequences of all states be considered. Thus, as the task complexity increases the optimization problem rapidly gets out of hand.

What are needed are relatively simple indices or relationships between task variables which are predictive of task performance. There are very few examples to cite, but one very useful such index is that attributed to P. M. Fitts, sometimes called the "index of difficulty" and equal to the log of the ratio of required move distance to required tolerance of final position. Examples of the use of Fitts' index will be cited in Section 7.

4. MANUAL/COMPUTER CONTROL

4.1 Modes of Servomechanism

Control means to make a thing do what is desired. There are two main problems in control:

1) to decide what is desired;
2) to make the thing do it.

With respect to the second problem, we may illustrate some common distinctions between modes of control by reference to Figure 4.1, which models a manipulator system as a conventional feedback control system or "servomechanism". If all of the feedback loops are closed continuously this is a force-reflecting master-slave position servo-mechanism.

Not all of the feedback loops need be closed. For example, assuming the human operator has an adequate visual feedback channel (y_1 y_2 y_3) in terms of spatial resolution and video frame rate, satisfactory control of a manipulator or vehicle or sensor position (x) may be achieved by the human operator by comparing what is observed to what is intended (r), deciding on the basis of this position discrepancy (e) what to ask (u_1) his muscle to send (u_2) to the joystick or other hand controls, which in turn communicate across a channel (u_3 to u_4) directly to an actuator, such as a hydraulic valve-cylinder device, which finally exerts a force (u_5) against a load or disturbance (v), the difference between which (u_6) drives a mechanical device to a position (x), depending upon its dynamics. In this case, assuming the position servo signal (y_0) and the force feedback channel (z_1 z_2 z_3) don't exist we have pure "rate control", where visual position feedback is the sole basis for achieving eventually a desired position, corrupted of course by disturbances in the y_1 y_2 y_3 or u_1 u_2 u_3 u_4 channels. In this case the teleoperator may be said to be under "open loop control".

Another form of open loop control is where the visual feedback loop is closed only intermittently and during a lapse of such visual feedback the operator commands a u_2 signal which he estimates to be appropriate. In this case, if position feedback y_0 is available, the measured descrepancy between it and command u_4 drives x into conformity with u_4.

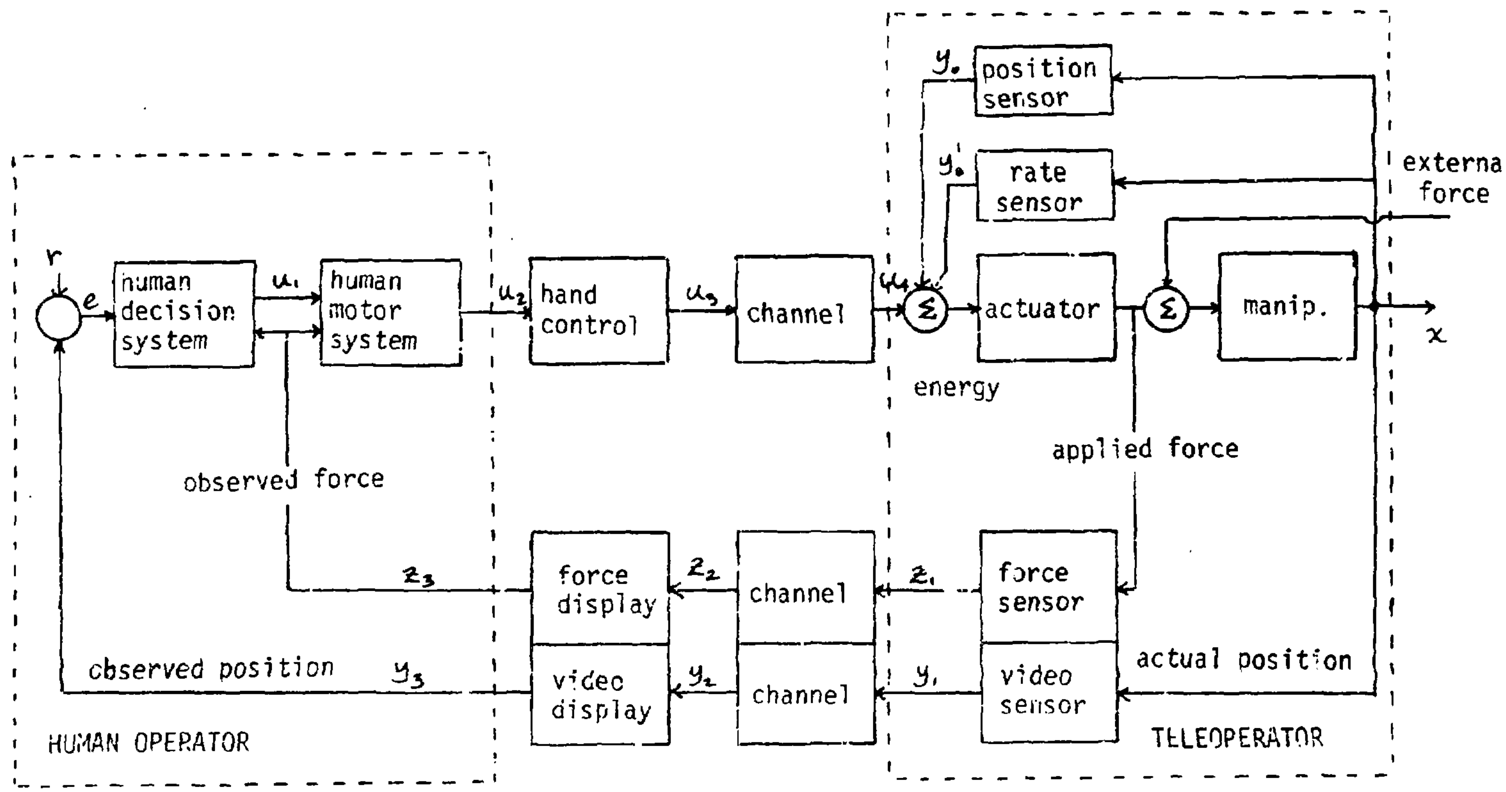


FIGURE 4.1 BLOCK DIAGRAM OF CONTROL LOGIC IN CONVENTIONAL FORCE-REFLECTING MASTER-SLAVE TELEOPERATOR SYSTEM

If the forces applied to the terminal device, and sensed either by strain gages, or by the armature current in the motor, are fed back to the operator's hand (through the z_1 z_2 z_3 channel, possibly modified in scale, hopefully not biased relative to zero) we speak of "force feedback". Such force feedback can be used with rate control (i.e., without position feedback y_0) or without visual feedback (y_1 y_2 y_3). Excluding both visual and artifically sensed position (y_0) feedback simultaneously would probably not be satisfactory except in certain cases where "pure force control" is desired, independent of position.

If force and both types of position feedback are available simultaneously, we have a conventional "force-reflecting master-slave position servo" as stated earlier. The term "bilateral" is sometimes appended when such a system is designed symmetrically, where the force display is actually a motor-driven hand controller, and where any position error between master and slave forces the slave hand in one direction and the master hand controller in the other. In most such systems either end can serve as the master, the other the slave.

It is not our purpose here to review standard control systems theory. Suffice to say that if each of the blocks in Figure 4.1 were describable by a linear differential equation, the whole system becomes amenable to analysis by conventional linear control theory - stability analysis, and so on. This is true even if each of the variables (lines) is a vector of many dimensions and the blocks are matrices of linear operators.

An "optimal" determination of the human operator's control strategy as a servomechanism can be determined by solving simultaneously the set of equations specifying all the physical transfer-functions in the system together with an equation specifying the optimal tradeoff between all relevant performance variables, e.g., x, e , time, and energy used. In practice this is usually easier said than done. However, if the element transfer-functions are linear, the tradeoff criterion is quadratic, and the disturbance time functions are Gaussian, it is straight forward, though complex. This is the subject of so-called "modern control theory".

Even if we have a perfect servo, i.e., x follows r instantly and faithfully with insignificant energy or other cost, the major problem remains that of deciding what is desired - deciding what motions to execute in what order.

Deciding what to do in what order is something people appear to be good at. It comes close to what is considered "motor skill" or even "intelligence". This is the reason that programming manipulators to do clever things is popular with the artificial intelligence community.

4.2 The Roles of the Computer in Teleoperator Control

It may seem, then, that if a human operator were available to decide what motions of manipulator, vehicle or sensor need to be executed in what order, then technological effort need only be concentrated on making servomechanisms closer and closer to perfection. This is not the case, or at least the situation is not quite that simple, and at least one other form of technology which is not considered to be part of the servomechanism per se, namely the computer, has very great promise.

A perfect servomechanism necessarily would have to include instantaneously responding actuators with no dynamic lags or static distortions, as well as a perfect visual feedback channel y_1 y_2 y_3 and a perfect force feedback channel z_1 z_2 z_3. To the degree that such motor and sensory channels approach perfection, to that degree the teleoperator system will become transparent to the human operator; he will see and feel himself to be controlling the manipulator as though he had a pair of pliers in his hand. Perfect manipulator design might further demand that the pliers be transparent - that the operator would then see and feel as though he were interacting with environmental objects with his bare hands.

A "perfect handling" vehicle control servomechanism would also demand extremely fast actuators and a high degree of both visual and force feedback and so too would that for positioning a remote sensor. In this case it is a bit more difficult to interpret what transparency would mean.

In any case, to achieve such transparency - to make it seem to the operator that he is present at the remote site with no apparatus intervening between himself and the end object of his control - in practice is not attainable. The computer can compensate for descrepancies in motor response and feedback in various ways. We might portray these computer roles in four categories, as illustrated in Figure 4.2:

1) the computer can also compensate for less-than-perfect decision-making or other capabilities; it can extend his capabilities to help the teleoperator accomplish more than if he alone were in control.
2) it can relieve him of some control tasks while he concentrates on others.
3) if video feedback is lost for brief periods the computer can provide back-up by taking over control.
4) it can replace him when a task can be programmed and is too dull or fatiguing to warrant his continued attention.

It is interesting to consider a continuum along which the "degree of automation" can vary from none (direct manual control by person) to complete (hypothetical intelligent robot with no intervention by person). The collaborations between human operator and computer we are considering obviously fall part-way along this continuum. Now we can make a qualitative plot (Figure 4.3) of the kinds of tasks each mix of human and computer control would be capable of, measured in terms of unpredictability or "entropy" (for example, in simple cases measured in information theory terms, using log signal-to-noise indices such as Fitts' law).

It is instructive to consider alternate design philosophies or "development trajectories" in terms of the two variables of Figure 4.3 replotted in Figure 4.4. The computer's function can be seen to compensate for feedback deficiencies in several alternate ways: In the (a) part of Figure 4.4 are shown three development trajectories, or avenues of improvement of teleoperators (ability to do more complex tasks). The trajectory labeled X shares computer control with the human operator to improve the quality of the continuous sensory feedback or motor feedforward; here essentially all control decisions are made by the human operator, see also diagram (b) below. Hence X shows little increase in control

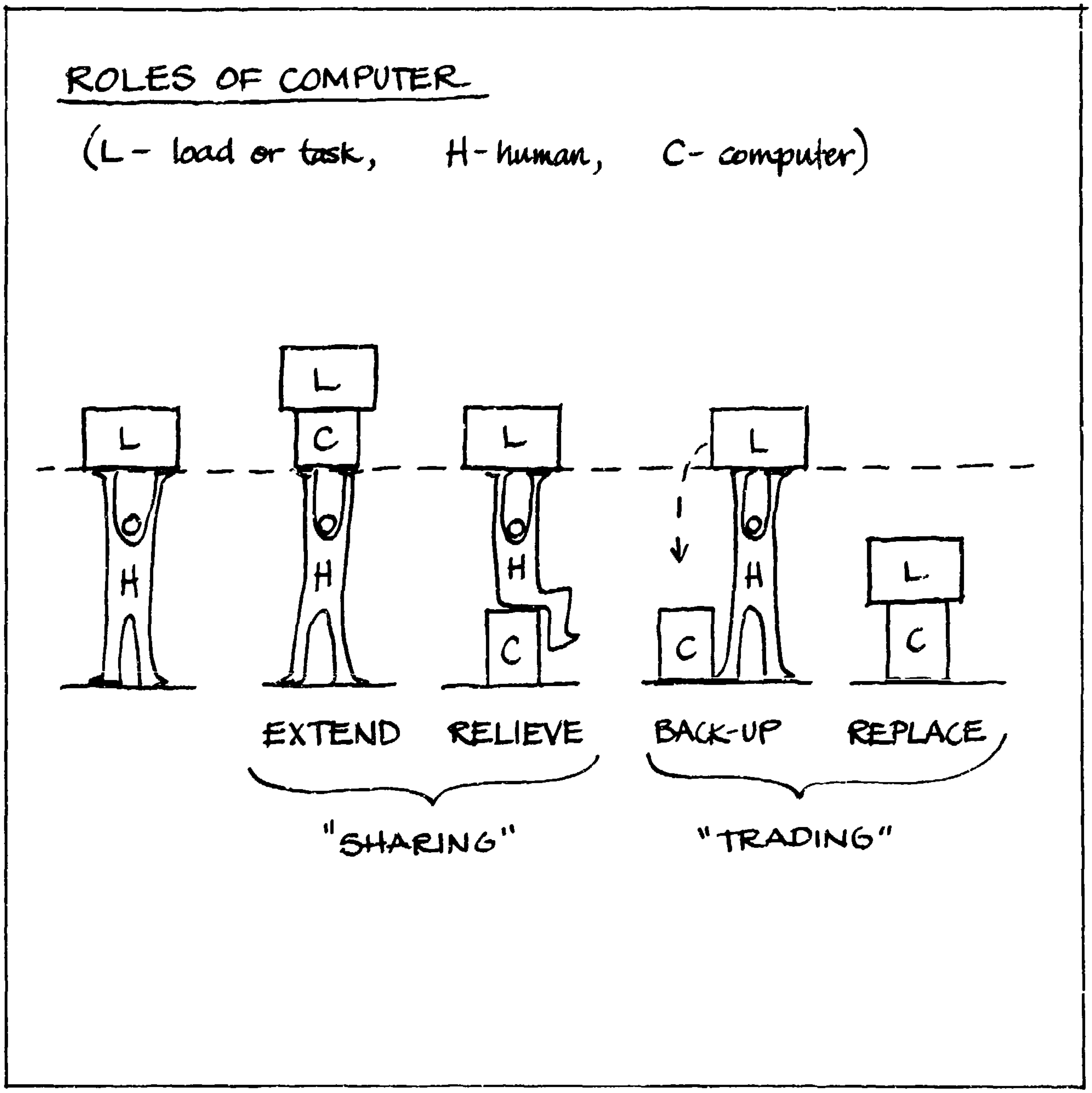


FIGURE 4.2 ROLES OF COMPUTER in supervisory control can be classified according to how much task-load is carried compared to what the human operator alone can carry. The computer can EXTEND the human's capabilities beyond what he can achieve alone, it can partially RELIEVE the human, making his job easier, it can BACK-UP the operator in case he falters, and it can REPLACE him completely.

In the case where both computer and human are working on the same task at the same time, we call this SHARING control. When they work on the same task at different times this is TRADING control. Different modes create very different demands on the human operator. (See Section 6).

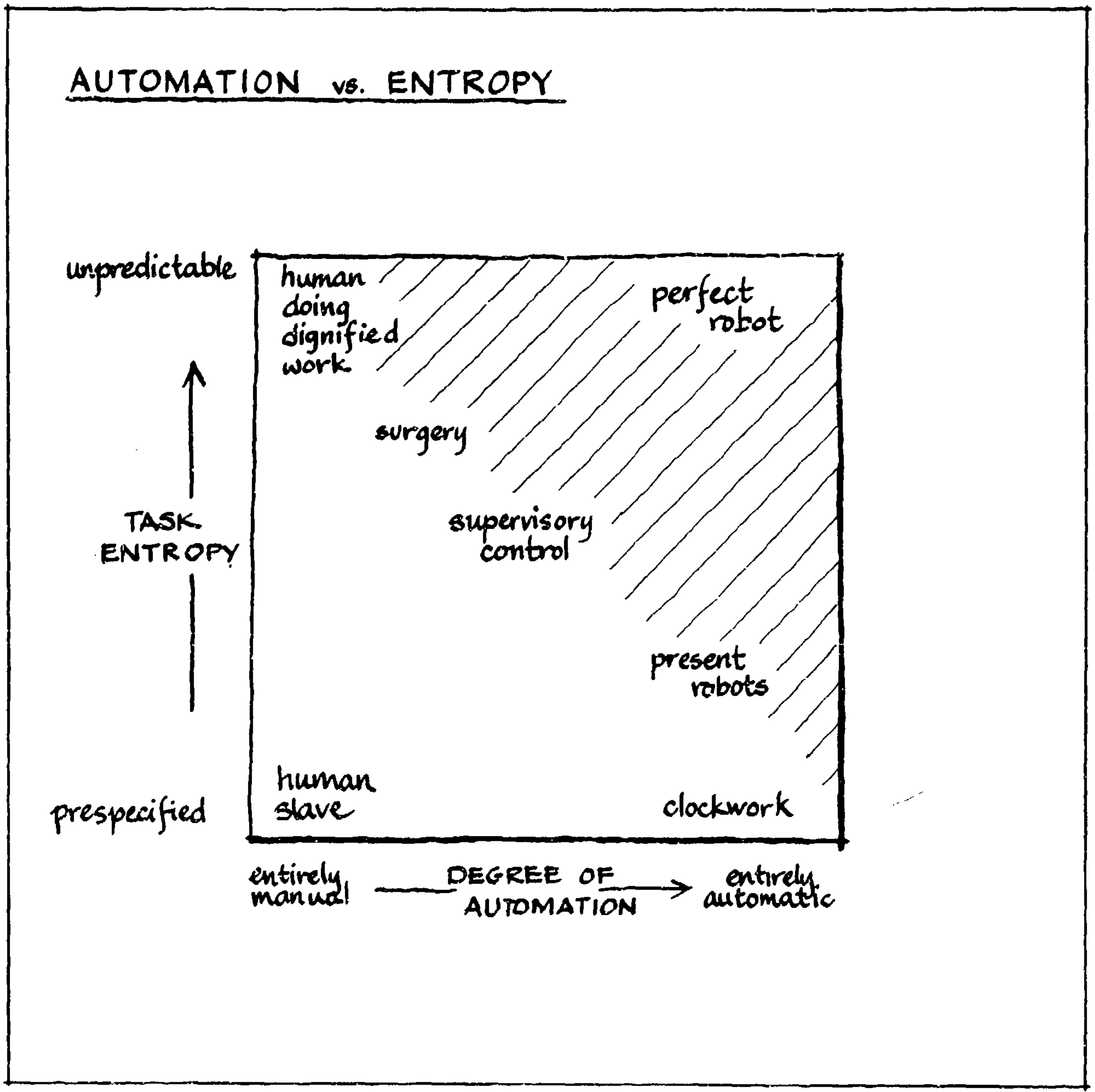


FIGURE 4.3 TASK ENTROPY (CAPABILITY) VS. AUTOMATION COMBINATIONS.
The upper left to lower right diagonal is a "frontier" of development.

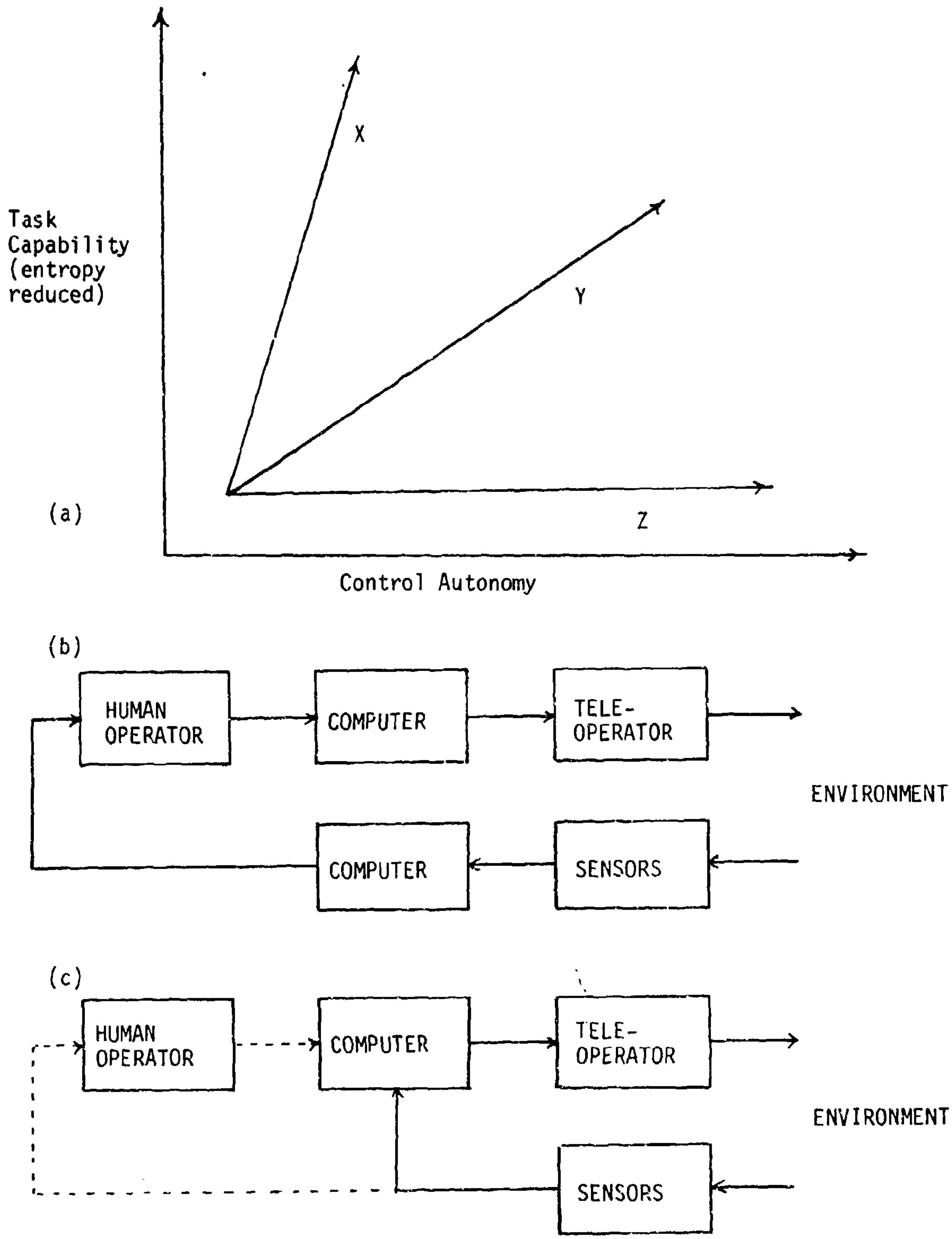


FIGURE 4.4 ALTERNATIVE DESIGN PHILOSOPHIES FOR TELEOPERATORS. For X control is mostly shared and autonomy increase is slight. For Y control is mostly traded and autonomy increase is large. For Z autonomy is added with no improvement in task capability. Design (b) shows man and computer collaborating in sharing mode. (c) shows control traded to computer, man acting as supervisor.

autonomy as task capability increases. This kind of improvement is called for in situations where there is no time delay, but visual and proprioceptive feedback is of poor quality. This is discussed at greater length in Section 6.

Trajectory Y trades control between computer and human operator, thereby gaining significant task capability when there is a time delay or visual dropout or for other reasons the operator cannot function as an effective continuous controller. This is the mode in which we have described supervisory control previously. Diagram (c) represents such intermittency of control through the human operator to the computer, while the computer mediates continuous control with the human. Along such a development trajectory the gain in task capability correlates directly with increase in control autonomy.

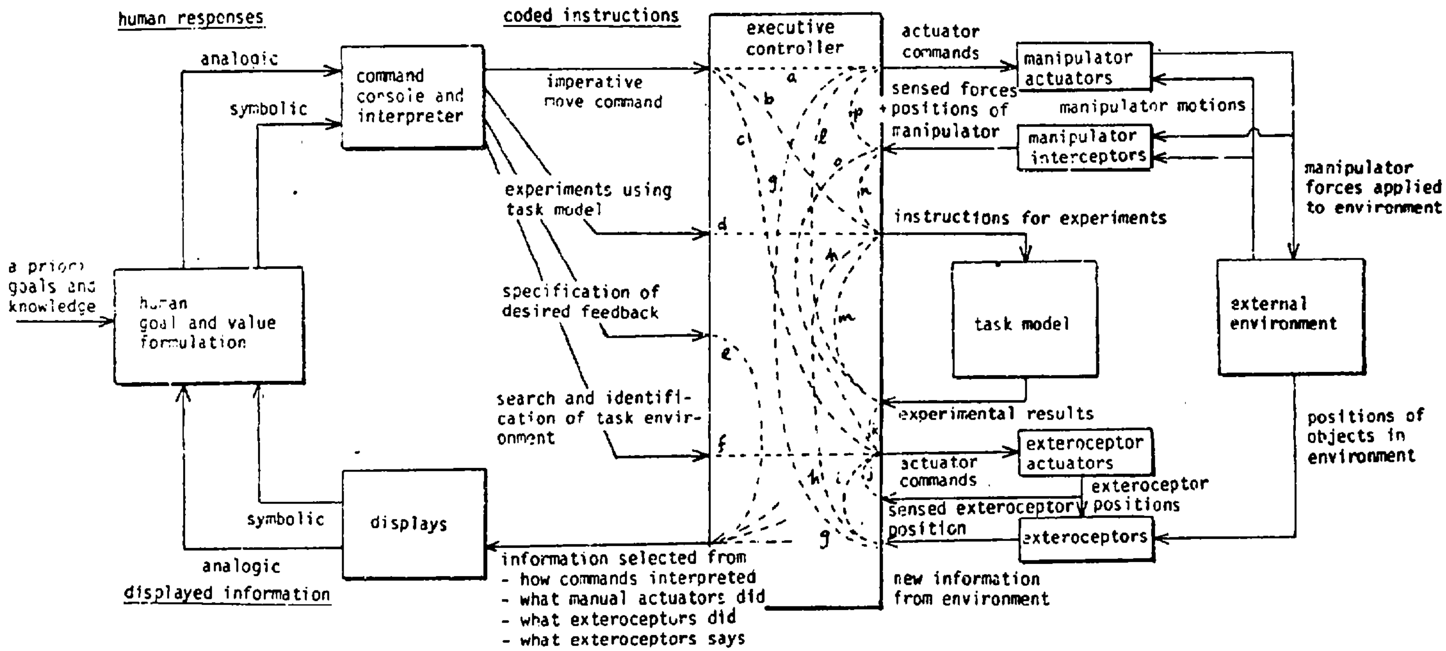
Trajectory Z shows increase in control autonomy without any increase in task capability. This corresponds to situations (also represented by diagram (c)) such as record-playback or other direct automation of human function, simply to back-up or replace the human operator in a task he can do by himself.

A more comprehensive block diagram of functions performed by the computer in relation to the operator and various physical elements of the system is given by Figure 4.5. The paths through the central "executive" block indicate the information source and destination for each processing function. Note the symmetry of sensors for effectors and effectors for sensors.

4.3 The Roles of the Human Operator in Supervisory Control of a Teleoperator

In such a supervisory control situation the human operator, like the computer, performs in different roles at different times, Figure 4.6. These are grouped into four role categories.

1. Command: to program a series of teleoperator sensing, mobility, or manipulation operations and commit these to action. These commands may be analogic (control forces and displacements which are geometrically isomorphic with intended system response) or symbolic (strings of alphanumeric keystrokes when strung together specify unique instructions). Either type of command may be directed toward teleoperator movements, or, short of that, toward computer executions of



a. direct instructions to manipulator actuators

b. instructions to perform task model experiments as part of move strategy

c. instructions to exteroceptor actuators as part of move strategy

d. direct instructions to perform experiments on task model

e. information selection for display

f. direct instructions to exteroceptor actuators as to where to look

g. manipulator control as a function of new information in the environment

h. updating of task model as a function of new information in the environment

i. modification of exteroceptor positions as a function of what exteroceptors sensed

j. feedback in automatic exteroceptor search

k. modification of exteroceptor positions as a function of task model experiments

l. manipulator control as a function of task model experiment results

m. execution of task model experiments as a function of previous experiment results

n. updating of task model as a function of where manipulator is

o. slaving of exteroceptors to view manipulator end point

p. manipulator position and rate feedback control

FIGURE 4.5 DIAGRAM OF FUNCTIONS PERFORMED BY COMPUTER.

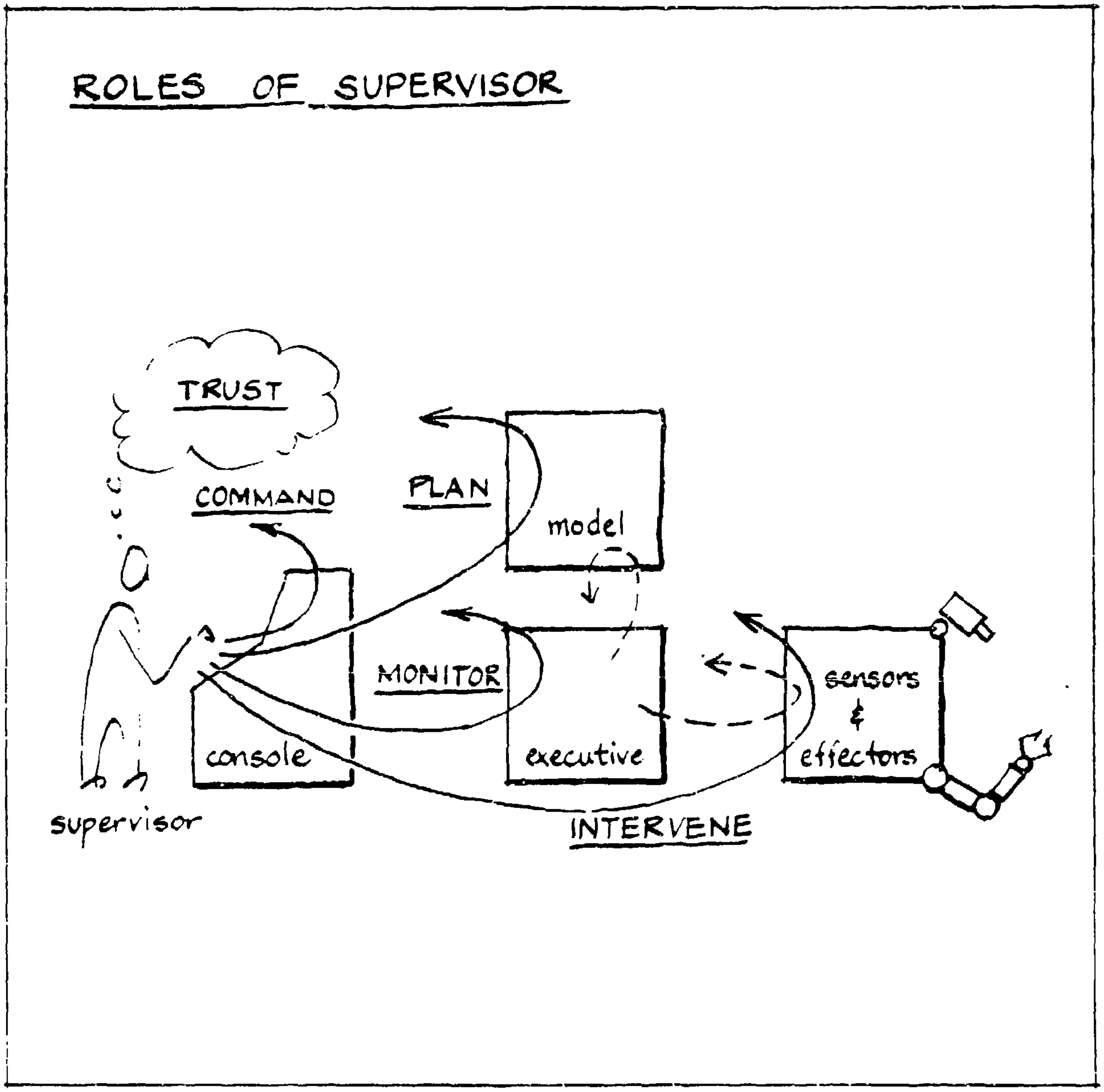


FIGURE 4.6 ROLES OF HUMAN OPERATOR IN SUPERVISORY CONTROL OF TELEOPERATOR.

displays of desired information in desired formats, or of program changes. The computer may help by checking out symbolic commands to make sure they are understandable. (The principal concerns for engineering this role are what combinations of analog and symbolic commands are best for what kinds of tasks, and what kinds of feedback signals from the computer will most help the operator compose appropriate instructions quickly and without undue "hassle").

2. Plan: to consider and evaluate various alternative future commands (for teleoperator actions). As part of the planning process the operator may try these out by commanding a computer-based model which implements the commands as "thought experiments" off-line in fast-time. The results, suggesting "what would happen if", can be displayed side by side on a graphics terminal for the human operator to compare. Non-computer models can also be used for such planning purposes such as maps, or three dimensional scaled-down models of the vehicle or manipulator or environmental objects which may be moved in relation to one another. Sometimes computer-based planning models and displays can be utilized simultaneously with control of the teleoperator; a predictor display (discussed later) is an example. (Our principal engineering concerns for this role are what kinds of models are most useful to the operator's planning, and what time-span or cycle-time of planning and action are best, again both depending upon task).

3. Monitor: to observe various displays of teleoperator performance while the latter is automatically implementing commanded actions; to adjust the displays to provide different presentations of data to be monitored; to make small parametric adjustments in control parameters; to instruct the computer to make on-line diagnoses. (Here we are concerned with how much and what detail to give the operator to help him keep track of the key variables. We are also concerned with problems of mental overload and underload.)

4. Intervene: to take over control manually; to change control to a mode more manually direct than would normally be the case; to cause the computer to shift into a preprogrammed "abort" mode; or to stop the teleoperator action altogether. (For this role the concern is what criteria are most appropriate for the intervention, what the transient response is likely to be under various task-teleoperator situations, and how the system can be designed to be "fail soft").

5. Trust: to attain enough operating experience or otherwise acquire a basis for believing that the teleoperator will behave as intended; to understand, come into temporal and spatial synchrony with, and identify or empathize with the responses of the teleoperator to various commands. (Here the concern is how best to help the operator acquire this identification. It depends on selection, training, and the naturalness and quality of feed-forward and feedback loops.)

Section 6 continues the discussion of supervisory control of teleoperators. In the next section we discuss the effects of hardware configuration on teleoperator control - in particular the hardware for sensing, communication, display, vehicle mobility, manipulation, and command interfacing with the operator.

5. CONTROL HARDWARE FOR: SENSING, COMMUNICATION, DISPLAY, VEHICLE MOBILITY, MANIPULATION, COMMAND.

5.1 Sensory Systems and Their Environmental Constraints

Optical Sensing

The most important sensory mode for teleoperation is optical, since video is well developed and directly interpretable by vision, which in turn is by far the richest sensory mode of the human organism. Table 5.1 indicates the most important physical attributes corresponding to: the video source objects, the communications channel (including water, video or sonic imaging sensors, electrical channel and CRT display), the display (physical stimulus impinging on the retina), and the corresponding behavioral (visual) response.

The ocean environment poses severe constraints on vision. Referring to the numbers in Table 5.1:

1. Illumination decreases as a function of depth, except for biological or man-made illumination.

2., 3. Reflectance and contrast of adjacent objects decreases as all objects which remain undersea become coated with the same plant matter and silt.

4 Colors all become similar for the same reason as 2.,3.

5. Patterns and textures similarly become one.

6. Range and orientation (lateral position in sensor field) are unknown or only partially known at the time of visual search.

7. Spatial resolution of the sensor (and channel) is usually far worse than that of the eyes.

8., 9. Turbidity (both density and particle size) of the water depends on location, but typically is the major factor in reducing visibility. Reduction is both by forward scattering (reducing brightness contrast) and by omni-directional scattering (small particles selectively scattering and reducing blues more than reds). In non-turbid water the reds are absorbed more quickly than the blues

TABLE 5.1 CONSTRAINTS ON VISION

ATTRIBUTES OF SOURCE OBJECTS	ATTRIBUTES OF SENSOR AND CHANNEL	ATTRIBUTES OF RETINAL STIMULUS	ATTRIBUTES OF VISUAL RESPONSE
Size of object	Range and orientation (lateral position) of sensor relative to stimulus 6	Retinal size of image	Initial detection of stimulus
		Retinal position of image	
		Accommodation to displayed image, retinal acuity	Resolution of detail
Illumination 1	Position of display relative to observer	Brightness of image	Identification of meaning
Reflectance 2			
Contrast of adjacent parts 3	Spatial resolution of channel 7	Contrast sharpness	
	Field of view	Dark adaptation	
	Opacity (turbidity) of water 8		
	Contrast enhancement or deterioration		
	Saturation of transducer		
Color 4	Differential filtering 9	Color of image	Teleoproprioception (see discussion in text)
	Computerized signal conditioning 10		
Duration	Frame rate and time delay 11	Duration	
Movement	Tracking capability; 12	Movement of image on retina	
Continuity of pattern or texture 5		Superposed graphics and alphanumerics	
"New information rate"		Expectation, familiarity	

(Vaughan et al., 1977).

10. A computerized signal conditioning can enhance contrast and improve some aspects of the picture but sometimes at a loss in gray-scale or other potential information.
11. Frame rate is usually faster than the eye's flicker-fusion frequency with tethered video, but may reduce to one frame per several seconds with sonic communication. Transmission time delay poses problems of correspondence between display and control (see Sections 5.2 and 5.3).
12. Tracking, i.e., keeping the video or sonar sensor positioned, oriented and focussed on a moving target, can be a difficult and time consuming task for the operator, and not always successful.

Other aspects of this table will be discussed later in this section.

Sonic Imaging

An alternative to video imaging is sonic imaging, whereby the differential sound energy impinging on each point in a two-dimensional array of accoustic transducers or a continuous surface of piezo-electric material is electronically converted to a video-type display. Because of the great reflective-dissipative property of sound in water, the placement and frequency of two or more sound sources, and the focussing of impinging sound through an acoustic lens and an aperture onto the transducer are critical. While the range of sonic imaging is severely restricted (e.g., not more than a dozen feet at the present), the fact that it is unaffected by water turbidity has motivated great interest. The art is yet primitive, however. An excellent recent review is by Sutton (1977).

Optic-Sonic Trade-offs

Whether for video or for sonic imaging, the trade-offs between range (distance from sensor to object), energy required, turbidity of water and resolution obtained are of major interest in control of teleoperators. Trade-offs between any two of these variables depend on the levels of the

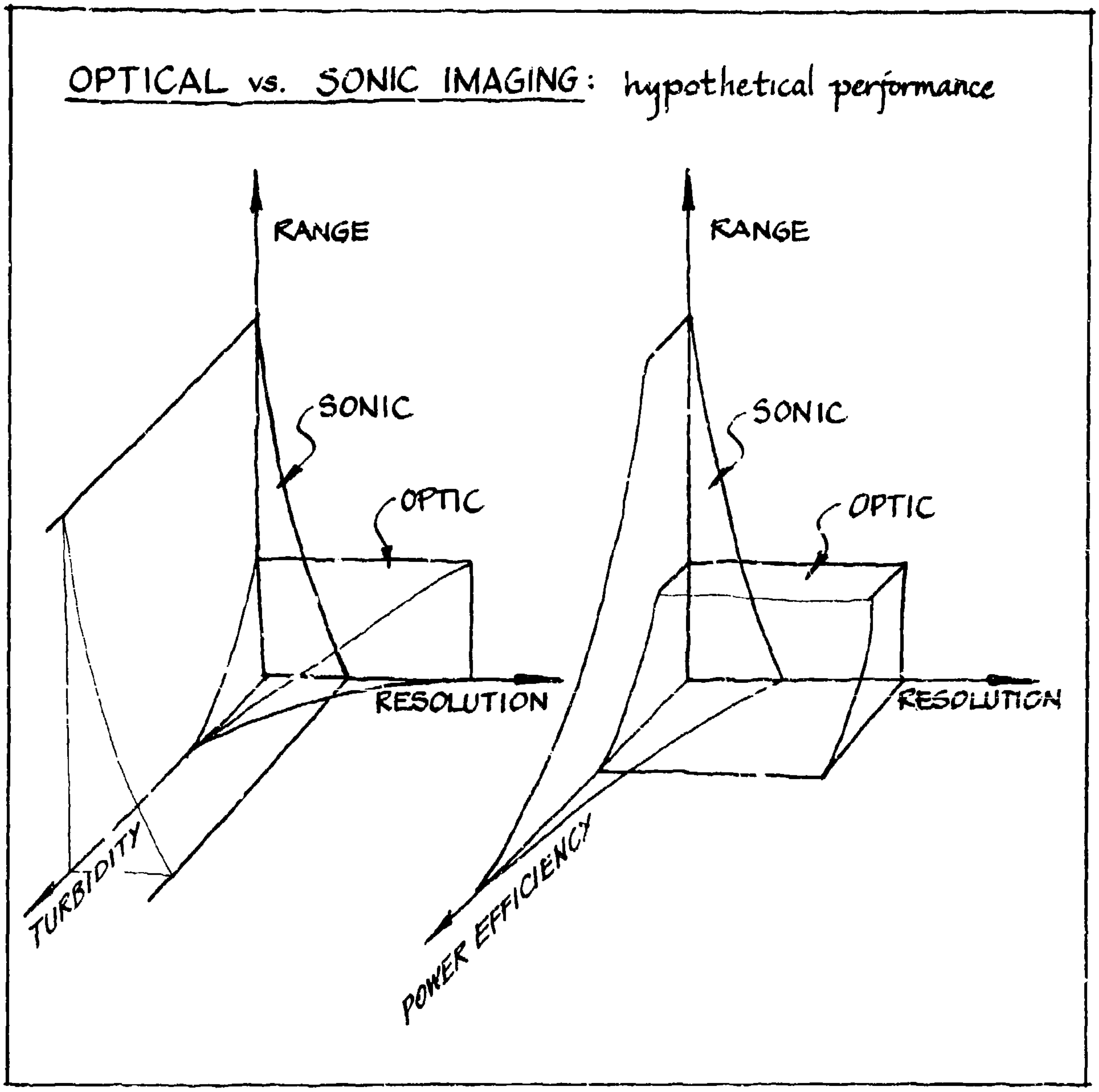


FIGURE 5.1 OPTICAL VS. SONIC IMAGING. These performance surfaces represent some of the trade-offs between optical and sonic sensing in water. The greatest resolution is for light but only out to a limited range. Acoustical performance does not degrade as turbidity increases (left graph), but does degrade as less energy is used for insonification (right graph).

Optical performance degrades rapidly with turbidity (left graph) but it is less dependent on the amount of power used than is the sonic system (right graph).

other variables as well as many other factors. In Figure 5.1 are shown two three-dimensional plots for the four variables, and on each are plotted trade-off envelopes for both video and sonic imaging, indicating for each a set of approximately equivalent combinations of the three variables on that plot for the given sensor mode.

Proximity Sensing

For the purposes of detecting close proximity of solid objects to a manipulator hand, to control a movement along but not touching a surface, or to avoid obstacles, proximity sensors are used. These can be based on optical (e.g., light emitting diode) or sonic transducers, in either case determining proximity on the basis of reflected energy.

Force Sensing

Another class of exteroceptors (sensors of energy imposed from outside the teleoperator system) have to do with mechanical forces imposed on the teleoperator, primarily on manipulator arms and hands. Sometimes these take the form of wrist-force sensors (multi-degree of freedom flexible elements with strain gauges attached to sense displacement, i.e., resolve force in each translational and rotational direction). The electrical current load on the drive motors of the arm and hand give the same information, after subtracting for friction, gravity and inertial forces and resolving forces through the complex geometry of multiply cantilevered linkages .

"Force sensors" usually convey only the integrated forces imposed on the teleoperator. In contrast, "tactile sensors" potentially convey the pattern of spatially differential forces applied to the teleoperator from outside, i.e., patterns of forces on the "skin" or surface of the manipulator's gripper. Control performance in the use of some of these sensors is discussed in Section 7.

There are many other sensors which perform specialized measurements on

variables such as depth, speed relative to ambient water, temperature, acoustic noise, gravity, salinity, nutrients, pollutants, etc. which form part of the teleoperator's sensor complement when needed.

5.2 Communication, its Control and Environmental Constraints

When a tether is used, communication between teleoperator and human operator is normally accomplished by electrical means, using a coaxial cable to carry video signals and control signals multiplexed, and often with power sent on the same cable.

Achievement of satisfactory signal-to-noise ratio is not normally a problem in such cases. The problem lies more with the mechanical properties of the tether - its size, weight, drag, and problems of playing it out, winding it in, and fouling. The use of kevlar type synthetics to provide improved strength to weight ratio is becoming increasingly prevalent.

Optical fibers provide the capability for extremely high bandwidths which add a measure of redundancy and still allow high bit-rate two-way communication between a local and remote computer. Improvements in coatings to reduce refractive radiation losses now allow use of light fibers to any depth, provided a few repeaters are used. If the optical tether, plus a sheath to provide tensile strength and abrasion resistance, are not accompanied by a tether to carry electrical power and/or mechanically pull up the submersible vehicle itself, such tethers can be smaller than conventional coaxial cable tethers by a factor of approximately ten in diameter and viscous drag.

When there is no electrical or optical communication channel, either sonic communications or direct conduction through the water are the communication options. The latter is too new to evaluate. The former has been a standard means for underseas communication for some time at relatively low frequencies, but as carrier frequencies (bandwidths) get higher and distances get longer the fraction of energy lost becomes so large as to be unacceptable.

Figure 5.2 shows the bandwidth normally possible for alternative undersea communication systems: fiber optics (3M bits per second and up), coaxial cables (300K) and acoustic communication (up to 30K depending on range). For each such system is indicated the trade-off between bits per frame (number of video lines makes it more graphical - regular broadcast TV is about 500) and frames per second.

By contrast to electromagnetic propagation, which is instantaneous on a human response time scale, propagation of acoustic signals may pose a significant time delay. Sound travels approximately 1600 meters per second in water. Considering round trip time delay this means that for each 800 meters of depth there is a minimum of a full second between the time a message is sent from the surface and the time any feedback of results of that message is returned to the surface. The time may be lengthened for any control signal by serial encoding and decoding at each end, including sharing (multiplexing) with other signals. Thus for 300 m depths, time delays might be 1/2 second; for 600 m depths, delays might be 1 second, and so on.

The reason why time delays in control loops are undesirable is that they cause instabilities. Specifically, for that frequency for which the time delay plus inherent dynamic lag is one-half cycle, or any higher frequency, if the loop gain exceeds one the system will become unstable. Human operators can avoid this problem by moving and stopping (thereby reducing gain to zero), but this makes direct telemanipulation cumbersome. Experiments by Ferrell, Black, Hill, Starr and others have clearly indicated that delays of 1 second may increase task times by four or more times. (Time delay experimental performance data are further reviewed in Section 7.)

5.3 Display

Conventional Picture Display Technology

Referring to the display column of Table 5.1, it is clear that display variables also make a critical difference in the vision of remote objects both for inspection and for manipulation. However, the human factors of CRT

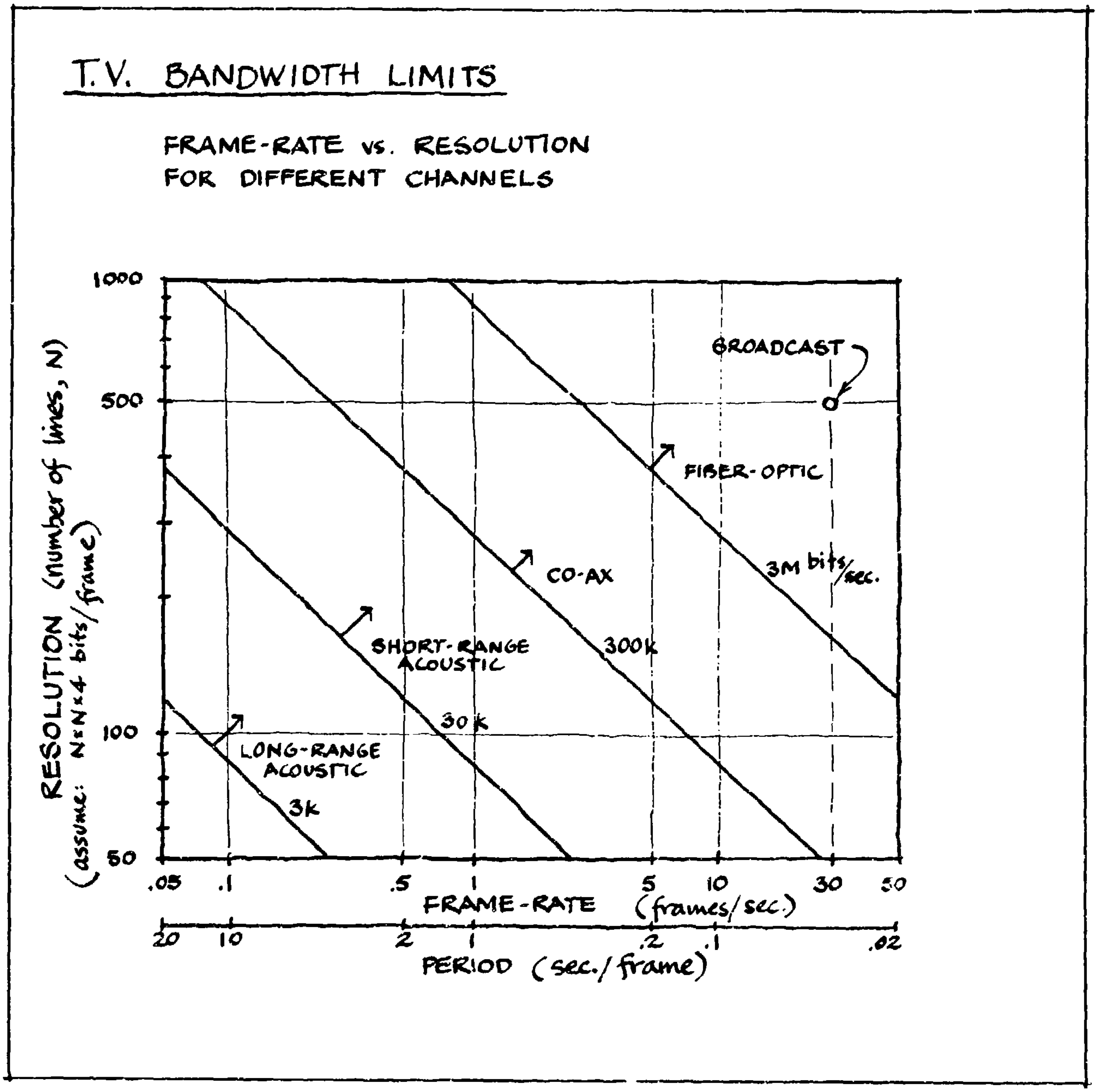


FIGURE 5.2 TV BANDWIDTH REQUIREMENTS. Normal broadcast television has a frame rate of 30 frames/second and resolution of about 500 lines. A long range (5 km) acoustic communication link for an untethered vehicle might provide a very grainy picture (50 lines) every 2 seconds or more resolution at greater intervals (e.g., 100 lines every 15 seconds).

Some important questions are: how communication restrictions affect task performance; for different tasks what is the appropriate trade-off between frame-rate and resolution; and whether the operator should be provided the capability to adjust the trade-off himself while operating.

and other displays are not unique to undersea operations. It may be said that the undersea application of new sophisticated visual display technology, computer generated graphic and alphanumeric information, superimposed on video displays or separately presented, has probably lagged behind corresponding aerospace application. If the display of such information is properly integrated, it can make navigation, power use, efficiency of search, etc. quicker and more reliable.

A specific example is the use of special predictor display technology where there are transmission time delays, as described in the next subsection.

Predictor Display Aids When There are Transmission Delays

For remote control, there are two sources of difficulty with sonar communications: time-delay and slow-frame-rate. Round trip time-delay is the time for a command to travel to the vehicle and the first indication of response to travel back. At a minimum this will be two times the distance divided by the speed of propagation, 2T. For example, T = 1 second at about 5,000 feet. Pictorial information from television camera or obstacle avoidance sonar will be further delayed because of limited channel capacity. Assuming a low resolution picture of 80 K bits and a channel capacity of 10 K bits per second, there would be at most one picture every 8 seconds (S = 8 seconds). The effects of trying to navigate with just this pictorial information are illustrated in Figure 5.3.

One way around this difficulty is a predictor display. Predictor displays were first investigated for submarine control (Kelley, 1968). NASA considered predictor displays for remote control of unmanned lunar roving vehicles, (Arnold, 1963) but sent men instead. A predictor display for untethered vehicle control would present a symbol superimposed on the slow-frame-rate and time-delayed picture from the vehicle's television camera. The symbol responds instantaneously and continuously to the operator's commands predicting "future" positions of the vehicle. For example, referring to Figure 5.3, when picture $\boxed{0}$ is complete the predictor symbol would show the position 1'. Before the next picture from $\boxed{1}$ arrives, the symbol will be

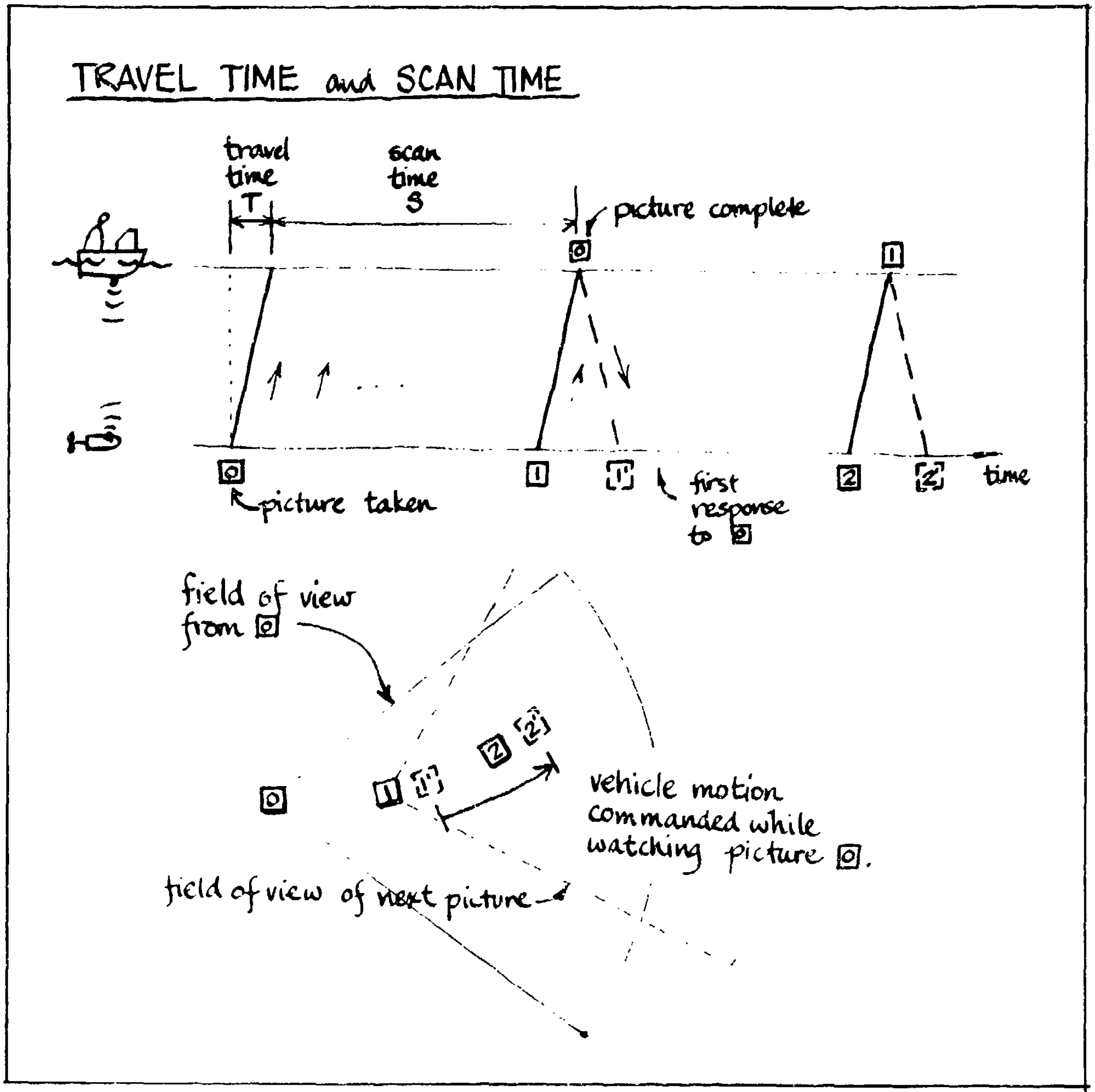


FIGURE 5.3 DELAYS IN PICTORIAL FEEDBACK for remote vehicle control through a sonic link are due to travel time (T, distance/speed of sound) and scan time (S, bits per frame/bits per second). The vehicle may have moved considerably from where the operator thinks it is.

The picture [0] is received T + S seconds after it is taken, the first operator response is received by the vehicle at least T seconds later, for a total delay of 2T + S seconds. While the operator is looking at the still picture from [0] the commands he is sending are actually moving the vehicle from [1'] to [2'], as illustrated in the lower map of vehicle motion and fields of view.

moved, in response to the operator's commands, to position 2'. The position of the vehicle is computed from a local model of the vehicle responses and from the operator's commands u(t), as shown in Figure 5.4.

The predictor symbol may prove useful both on pictorial displays (superimposed on television or obstacle-avoidance sonar) and on map-like position displays. Map displays would avoid one difficulty of pictorial displays, which is losing the predictor symbol when it moves out of the field of view of the camera (for example, moving sideways or backward).

If position data is available from transponders or locator beacons, it could be used to update the vehicle model. With just the pictorial data, the open-loop prediction would have to span an interval of (at least) 2T + S to (at most) 2T + 2S seconds. With auxiliary feedback the open-loop estimate will only need to span the delay of that auxiliary data (at minimum 2T). The signals and corresponding delays are shown in Figure 5.4.b. (u(·), command vector; x(·), vehicle location data). Another feature that could be built into the local model of the vehicle is some estimate of the disturbances (such as current). The model of the current as well as the vehicle model could be updated on the basis of the mismatch between predicted and measured vehicle position.

One unexpected finding from simulation experiments (Verplank, 1978) was that rather than sending the picture periodically every eight seconds sending the picture only upon the operator's request reduces the total number of pictures necessary and encourages a "move and wait" strategy which avoids confusion. The difference is illustrated in Figure 5.5.

On an actual vehicle, probably both modes should be available with the request mode used when move-and-wait strategy is appropriate (for precise positioning based on pictorial feedback, and when environmental disturbances are small). Periodic mode is probably more appropriate for less precise navigation and continuous motion when the predictor symbol can be relied upon. Another trade-off that should probably be built into the pictorial feedback is variable frame-rate/resolution. In a more dynamic and uncertain environ-

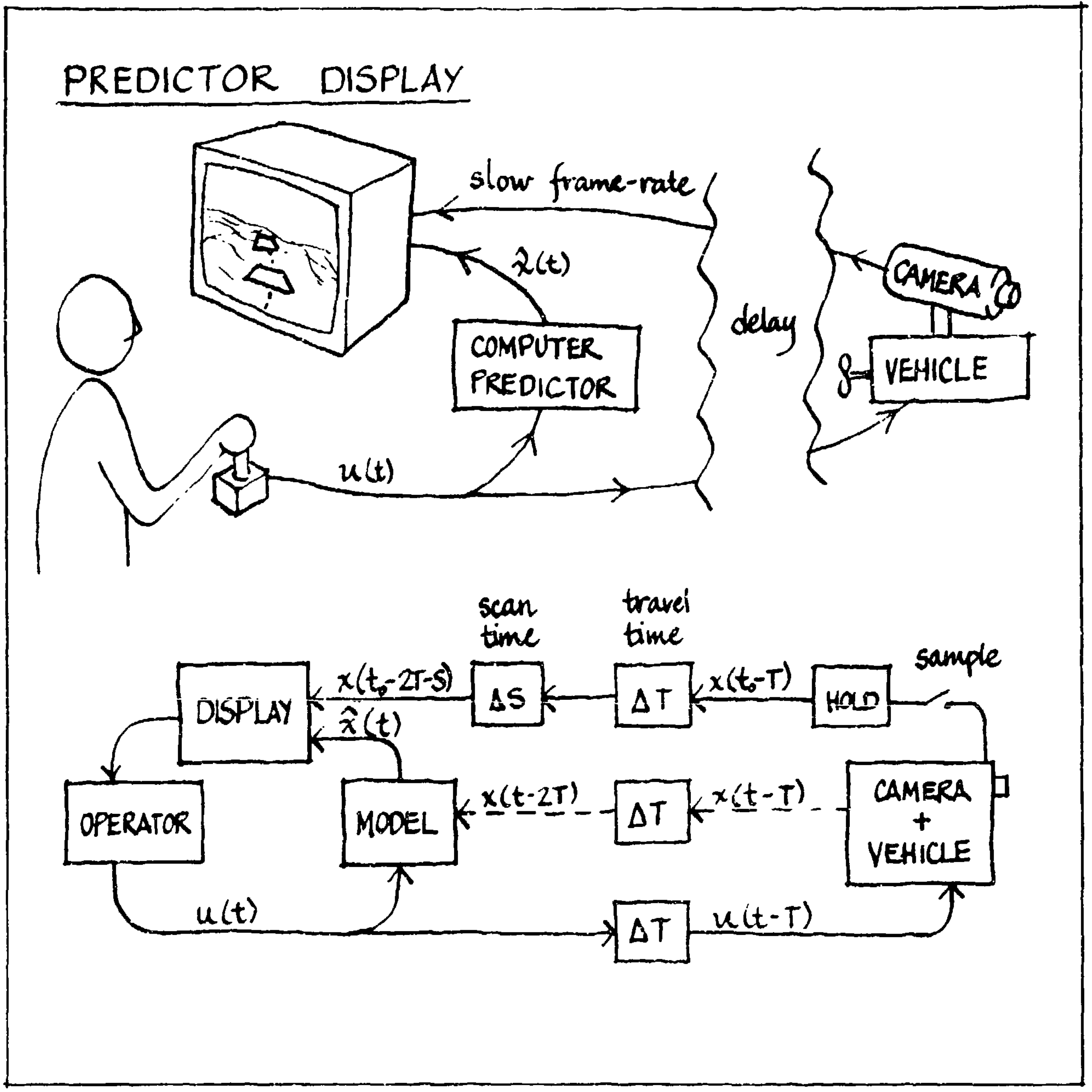


FIGURE 5.4 PREDICTOR DISPLAYS present the operator with dynamic information important for good control which he would otherwise have difficulty estimating. For example, a sonic link might give delayed (time T) and slow-frame-rate pictures (5 seconds/frame) at least 2T + S seconds "old". A local computer model of the vehicle's response is used to calculate and display the "current" estimated position of the vehicle, $\hat{x}(t)$ on the basis of the operator's commands u(t) and possible auxiliary position data (x(t - 2T), dotted line). The predictor symbol could be displayed in perspective superposed on the delayed picture. (Verplank, 1978).

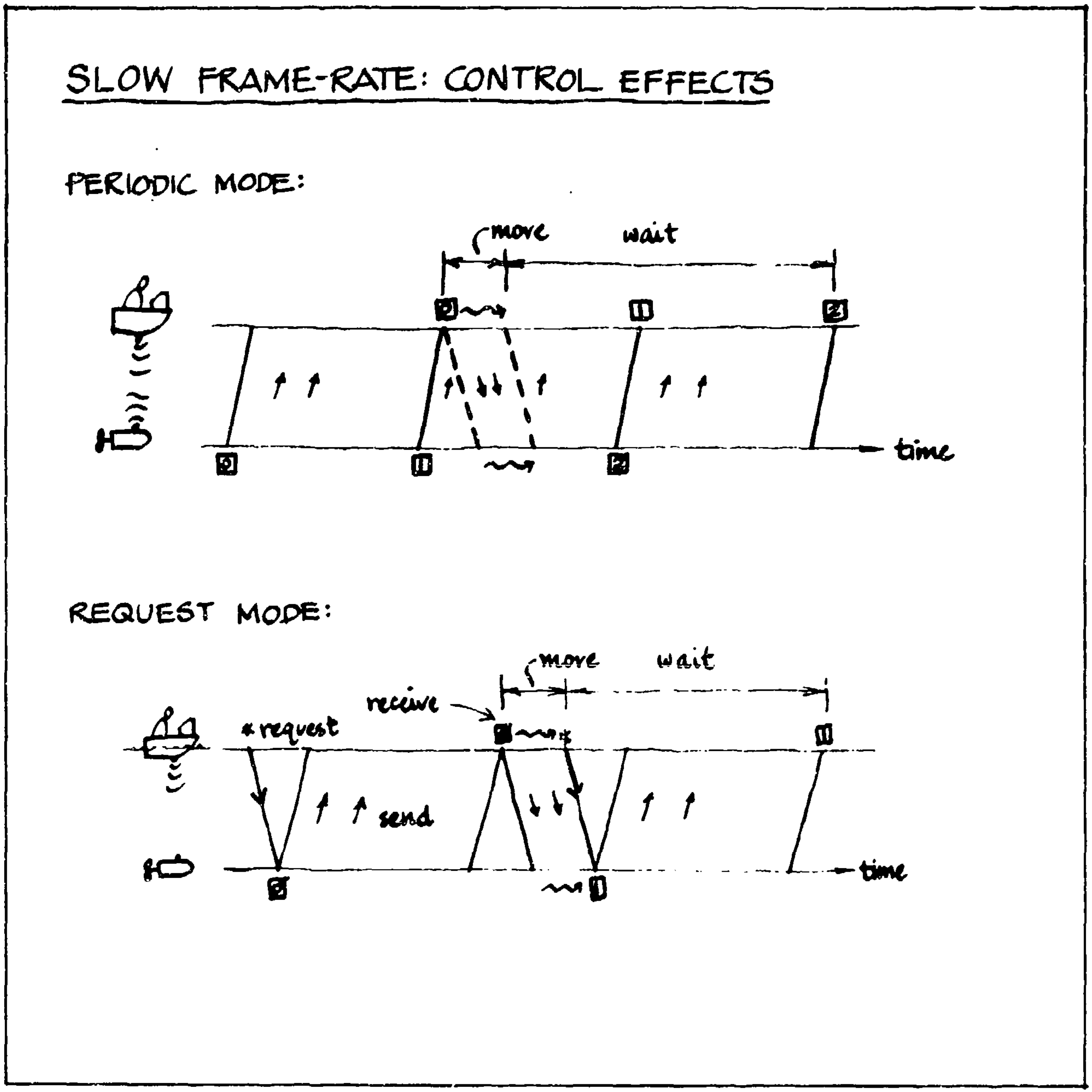


FIGURE 5.5 SLOW FRAME-RATE PICTURES could be sent, either continually (every 5 seconds in a "PERIODIC MODE", or only upon the operator's command "REQUEST MODE". It has been discovered that there can be a large effect on the quality of control, with or without a predictor display (Verplank, 1978).

In the periodic mode a short move starting with the receipt of picture $\boxed{0}$ will not be reflected in the next picture, $\boxed{1}$, as the operator might expect; instead he has to wait for $\boxed{2}$. In request mode, the wait for pictorial confirmation is minimized.

ment (i.e., larger bandwidth disturbances or target motion) sampling rate will want to be higher at the expense of resolution.

Display of Integrated or Differentiated Forces

The most natural display for integrated (resultant) forces imposed on the manipulator is the bilateral or force-reflecting master-slave manipulator. Forces can be scaled to be some constant proportion of (usually less than) the imposed forces, and if desired, the positional differences which correspond to the force differences can also be scaled through use of a smaller size master than slave. Display of wrist forces (6 degrees of freedom) and tactile forces (spatial distribution at various points on the manipulator hand) is more difficult. Experimenters with such devices usually have chosen to display such information visually (though there is difficulty for experimental subjects to make the cross-modality transfer from what would normally be muscle senses or cutaneous senses to vision). Cutaneous display of forces on the same hand as is controlling a master-slave manipulator has not yet been demonstrated successfully; supervisory (computer) control of manipulation may make it practical for a monitoring operator to assign one hand to feel the forces that the remote manipulator feels.

5.4 Vehicle Mobility, Navigation, and Vehicle Use as a Platform for Manipulators and Sensors

Dynamic and control aspects of submersible vehicles in general are beyond the scope of this report. However, the remote positioning of video or acoustic sensors and the remote control of manipulators are a function of vehicle motion.

Some submersibles are made specifically for inspection only - moving a video camera to proper position and holding, or moving continuously to scan a cable or pipe or structure. Whether the vehicle is tethered or not, inspection poses significant problems for teleoperator control. This is so for several reasons. One is that, while operating where there is plenty of light and the medium is completely clear one need only use a zoom lens to bring the view "close-up". When the medium has suspended particles which reduce

visibility one needs to swim up close for a decent view. But swimming up close may be hazardous because of collision, or because of danger of fouling a tether. A second reason is that ocean currents may be so strong as to prevent "hovering" without a large expenditure of energy; continually drifting past the object of attention may be a frustrating way to do visual inspection.

When the teleoperator's task is to manipulate, as well is to observe, the problems may be more severe. To perform mechanical work on an object, i.e., apply forces with manipulator, there must be some mechanical way to resist the opposing forces which necessarily occur on both manipulator and environmental object. If both vehicle and environmental object are resting firmly on the bottom, this may be no problem. But if either is not resting firmly, i.e., is free to rock or glide or is being pulled by ambient current forces on both vehicle and tether, or if either is free-swimming, it is necessary to employ one or more 'grabber arms' to hold the environmental object relative to the manipulator. These can be simple manipulators, with fewer degrees of freedom and less dexterity than the work-manipulator. But one must first find a place to grab. Further, once having grabbed, a pivot point is established; forces applied by ambient currents or by the manipulator may tend to rotate the submersible and task object relative to one another around the pivot point. This is especially serious if the submersible or the task object is large, where movement is slow and unnoticed in the acceleration phase, and stopping such motion abruptly to stabilize a critical manipulative activity is not possible.

Often both the submersible and the manipulator are controllable in six degrees of freedom. This means there is redundancy, and possibly control of the vehicles' degrees of freedom can be used to replace or augment the manipulator's degrees of freedom. Little significant work has been done as yet on this topic.

Manipulator arms and associated video sensors can be "packaged" in a structure which itself can be easily attached to and detached from one or more submersible vehicles. This permits a variety of work platforms, depending on

depth and other conditions, and does not burden any one vehicle with having to carry extra equipment when not needed. An example is the Navy's "Work Systems Package", a description of which is quoted below (Bertsche et al., 1978).

> "The Work Systems Package (WSP) was developed and fabricated under the Navy's Deep Ocean Technology Program and is designed to provide a versatile work capability to depths of 20,000 ft. The WSP is a group of manipulator arms and tools integrated into a modular package that will provide a heavy duty work capability when mounted as a unit on the Navy's CURV III or RUWS unmanned cable controlled submersible vehicles, and the ALVIN, SEACLIFF and TURTLE manned vehicles. In addition, it can be positioned and controlled by divers or operated independently from a surface support ship for operations at shallow depths without the necessity of resurfacing for tool interchange. Potential tasks include salvage, recovery, installation, and repair operations. Basic components of the work package include two simple outer manipulator arms without elbow functions that act as 'grabbers' or restraining/holding arms to steady the vehicle or hold small work pieces. A centrally located seven-function manipulator arm can select, interchange, and operate a variety of hydraulically-powered, explosively-actuated, or electrically-actuated tools, Included in the tool storage box are tools to perform cable cutting, synthetic line cutting, nut torquing, jacking, prying, wire brushing, sawing, grinding, drilling, chipping, and stud driving. An electrically-driven hydraulic pump unit supplies the power to a majority of the tools. Electric power is supplied from a self-contained battery package. Control of all operations and functions is provided through a multiplexed telemetry circuit from the vehicle. Pressure insensitive electronic circuits and pressure compensated hydraulic components allow all systems to operate at full ambient pressure."

5.5 Arms and Hands Design and Control

While our purpose in this report is not to be concerned with mechanical arm and hand design per se, there are aspects of arm and hand design which are important to man-machine control.

Most manipulator arms have six degrees of freedom from shoulder to wrist - just enough to place the wrist at any position and orientation within a working envelope. The larger the working envelope the larger the manipulator and, usually, the slower. Some manipulator arms have only four or five

degrees of freedom between shoulder and jaw, allowing the end effector to make up for, say, wrist rotation by having its own wrist rotation or drilling possibility, or allowing the angle of grasp to compensate in some way for one degree of freedom.

Figure 5.6 illustrates two popular types of kinematic design - the one consisting entirely of rotary joints, the other including one prismatic joint. Prismatic joints accommodate to hydraulic control because linear piston-cylinder actuator combinations are simple; however, prismatic bearings present problems. Rotary joints of course, can be actuated by linear piston-cylinders on linkages, or by rotary hydraulic motors, which have seen much improvement in recent years.

The distances between joints, and the types of joints, whether rotary or prismatic, directly determine the limiting envelopes or "approach angles" which constrain the orientation of the last link as the terminal device approaches a required point. The necessary configuration of the other joints - elbow, etc., are also thus determined - which is important in case the manipulator's working space is not free but constrained by objects to be "worked around". The kinematic analysis of such problems is presented formally by Roth, Kobrinskii and others (Sheridan, 1976).

The design of the kinematic linkage from shoulder to wrist is predicated not only on kinematic considerations for reaching a given point and orientation in cartesian space and avoiding collision of intermediate linkages, but also on considerations of statics (beam defection analysis), dynamics (oscillations due to mass of the arm, viscoelasticity of solid and fluid suspension) and motive power, (e.g., maintaining sufficient static-force to hold up a weight against gravity while in outstretched position; also the attainment of sufficient slewing speed).

Design of the hand, or, more generally, the "terminal device" is usually regarded as a separate problem. One philosophy is to have a very general purpose hand with at least grasp and possibly other degrees of freedom (e.g., bending fingers). The alternative philosophy is to have a whole "tool-box"

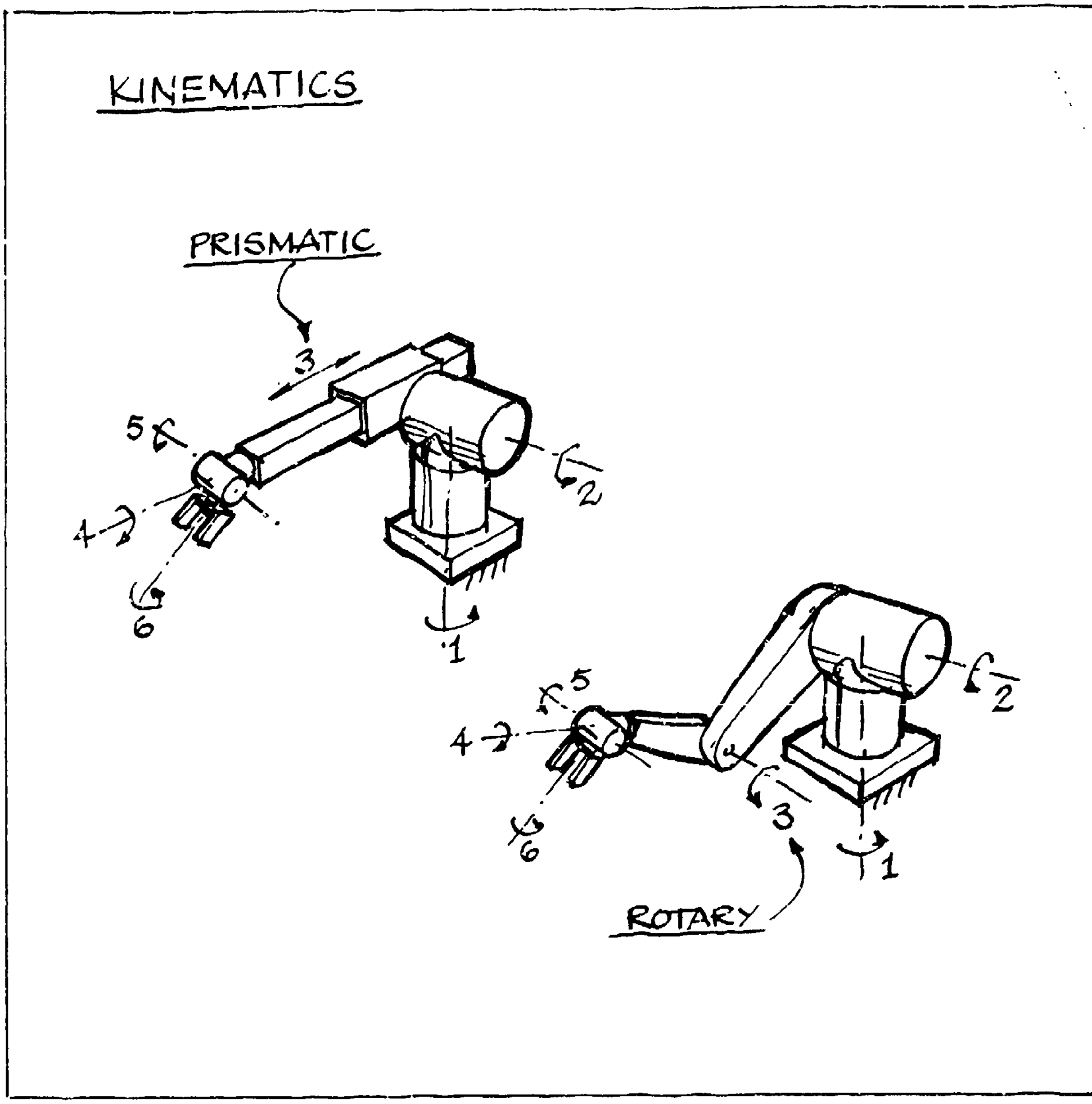


FIGURE 5.6 MANIPULATOR KINEMATICS generally fall into two classes, those with elbows (e.g., all ROTARY joints) and those without (e.g., one PRISMATIC joint). There are open questions about which configurations are best for computer-control (Roth, 1976) and which may be best for human control.

of power-driven terminal effectors any of which can be changed for another under remote control in the process of doing work. The Navy's Work Systems Package has a number of such end effectors, which can be stowed in the tool box by applying enough force (which breaks the hydraulic link but re-seals the supply tube so that minimal hydraulic fluid is lost). A different terminal device can then be attached, hydraulic pressure can be applied to it, and it can be removed and used. Brushes, saws, drills, taps, torque wrenches and compact hammers are popular terminal devices, in addition to "grabbers".

Any open-chain or series kinematic linkage will suffer from the common mechanical problems of droop under load (due to its own weight plus thatof load), static friction, hysteresis (backlash) and vibration. These problems will be different for each combination of arm configuration and load; and electromechanical position sensors in the joint articulations, depending on how they are connected, will not necessarily indicate the extent of these problems. These factors pose significant difficulties for maintaining end-point accuracy in a manipulator under computer control, if it is without some means to detect the actual position-orientation of the end point. When a human operator is continuously observing and controlling such a manipulator, however, the correction of such a lack of isomorphism between the "program" and the master end and the actual behavior at the slave end occurs relatively easily and naturally.

5.6 Command Hardware, Analogic and Symbolic; Teleproprioception and Anthropomorphism

By command hardware we mean those devices by means of which the human operator communicates his will to the computer and/or teleoperator. Such communication can be through voice-activated devices, through pedals, through electromyographic signals, or through other body "pick-ups". But hand-control predominates.

Hand controls can be either of two types: analogic or symbolic. Analogic controls are those for which the operator's hand motion is in some way

physically analogous or isomorphic to the display response desired: moving a joystick left to command leftward motion of the display and at a rate proportional to the magnitude of the joystick movement. Master-slave position controls, either full-size or replica, are analogic. Knobs and sliders are analogic. Switches which are mounted so that the direction of throw corresponds to display movement direction may be considered analogic.

Symbolic controls, by contrast, are not particularly physically isomorphic to the events commanded. Depressing a button does not mean the response observed on the display moves down. For symbolic coding - what keys are depressed in which order and in what combination with other keys is what determines the displayed response. Similarly, voice commands are symbolic; the sounds have given meanings which, as sounds, are not physically isomorphic with those meanings.

An important and time-honored human-engineering principle is called "stimulus-response compatibility". The events observed on the display should have a "natural correspondence" in time and space with human responses made or called-for. If this "natural correspondence" is not present the human operator tends to get confused and make errors.

Compatible direction-of-movement relationships will improve the performance of any man-machine system by improving the following: reaction time or decision time, the correctness of initial control movements, the speed and precision of control adjustment, and learning time. These improvements are relatively unimportant if the operator has a simple repetitive task, but their importance increases with the following: the complexity of the task, the discontinuity or number of interruptions in the control sequence, the degree of stress or anxiety experienced by the operator (Morgan, et al., 1963). All of these considerations seem pertinent to the present situation, and support the inclusion of compatible analogic controls in the command hardware for computer-aided manipulation.

Achievement of "stimulus-response compatability" is not accomplished automatically by analogic controls, nor is it impossible to accomplish

with symbolic controls. If valves in a chemical plant were controlled analogically by knobs, and the feedback of valve openings were displayed on a control panel directly adjacent to or in spatial isomorphism to the knob, this might produce satisfactory stimulus-response compatability. If the displays were layed out in a matrix with rows labelled by letters and columns by numbers, then a keypad with letters in series from A to Z and numbers from 0 to 9 might also provide stimulus-response compatability even though two or more keys might be required to select a single valve and the key positions would not be isomorphic with display positions.

The situation in teleoperator control is compounded by the need to control many degrees of freedom simultaneously, in a process which is physically remote from the operator, not always in view in the display, and possibly delayed in time. And sometimes (as with direct switch-actuated rate control) as the teleoperator moves relative to the video camera, the observed response direction of its movement (of, say, the manipulator arm) for a given direction of hand control movement changes. In other words, continuous display-control compatability is not possible with such controls; the display is not to be taken as indicating what to do next.

For these reasons the operator can lose track of the present true configuration of the teleoperator relative to where it should be, relative to what he observes on the display, relative to what control actuations he should make, and relative to his own body.

If the teleoperator is designed to be anthropomorphic, the operator tends to identify his own body and his immediate environment with the remote vehicle and its environment; he identifies his own arm and/or the hand-control or master-arm with the remote arm attached to the vehicle; and he identifies his head orientation with the orientation of the remote video camera (which of course is producing the video display he is looking at). His "bridge" to inferring what is going on in the remote environment is what he sees happening in the display (i.e., the position and orientation of displayed remote arm and manipulated remote object) and thus the correspondence between the display and his body movements is critical. This effort to maintain awareness of the teleoperator and its environment by

relation to his own body and its environment we call "teleproprioception". Teleproprioception is believed to be of great importance for control.

Figure 5.7 represents, by means of vectors to indicate the positions and orientations of the various important components, and by identities relating these vectors to each other, the isomorphisms which obtain for perfect correspondence (ideal teleproprioception). The more of these identities which hold, or the more accurately they hold, the better. For example, $C - B = A - V$ means that the control movement relative to the operator's body corresponds to remote arm movement relative to the vehicle. Figure 5.7 is intended only to suggest the beginnings of an analysis of this problem. The effects of lack of isomorphism need to be studied in detail.

It has been shown empirically that small deviations from the above isomorphisms can be compensated for quite easily by the operator. For example, Vertut (1976) showed that if the master end of a master-slave manipulator is rotated 30° relative to the slave (and all other correspondences left undisturbed) the operator could compensate, but as the disparity went beyond 45° performance deteriorated badly.

Various experimenters have employed head-mounted CRT displays to which the remote camera is servo-positioned; this ensures that the operator's head orientation relative to his body corresponds to the camera's orientation relative to the vehicle, and what he sees in the display is as if he were physically present at the camera mount on the remote vehicle. Unfortunately these experiments have not proven particularly successful due both to the bodily encumbrance of head-mounted displays and to poor mechanical tracking of remote video camera to head. Experimenters in the USSR (Yastrebov and Stefanov, 1978) have placed the operator in a cab which pitches and rolls in relation to vehicle pitch and roll to provide vestibular cues for teleproprioception.

In continuous man-in-the-loop control anthropomorphic teleoperator design is obviously important. But anthropomorphic design becomes less important as 1) control becomes more autonomous, and 2) control becomes

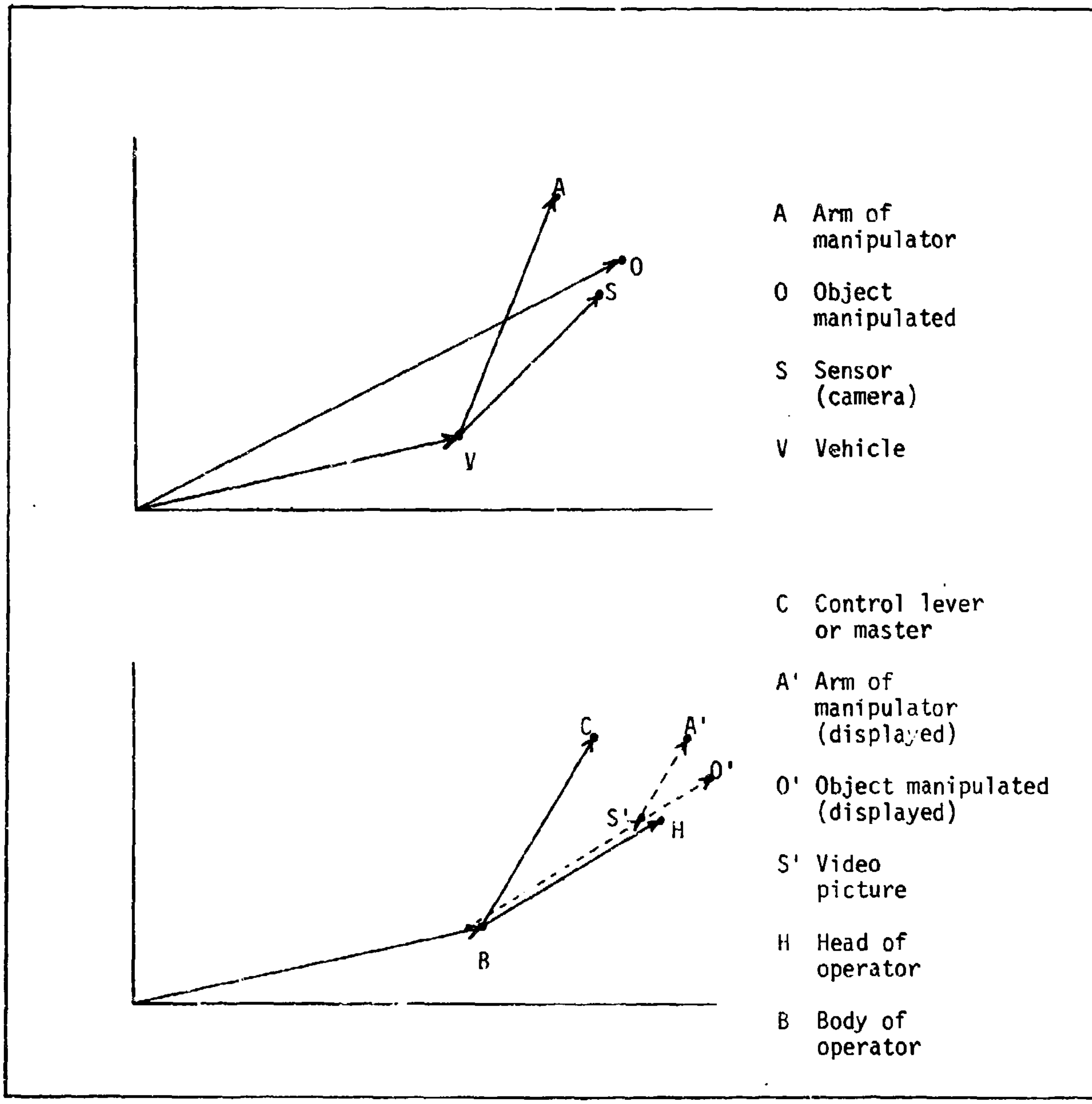


FIGURE 5.7 ISOMORPHISMS REQUIRED FOR TELEPROPRIOCEPTION. Vectors represent positions and orientations of vehicle, camera, manipulator and manipulated object (all at remote site) and of operator's body, head and arm, and display of remote manipulator and object (all at local site). Identities below indicate correspondences which hold for perfect isomorphism.

$B = V$

$S' - B = S - V, \quad S = H$

$C - B = A - V$

$O' - B = O - V$

more predictable. If the dimension of anthropomorphism is added qualitatively to the two dimensions, task entropy and control autonomy, by which teleoperators were classified in Figure 4.3, Figure 5.8 results. The hypothetical rectangular solid of all teleoperators is truncated on the lower left (sliced front-to-back) because ethically we seek to avoid assignment of people to such low level undignified tasks. It is truncated by the upper right front-to-back slice because we aren't yet clever enough to build such systems, and it is truncated by a right rear inward-slanting top-to-bottom slice because of the abovementioned absence of need for anthropomorphism. That is, automatic teleoperation could just as easily be accomplished by non-anthropomorphic design.

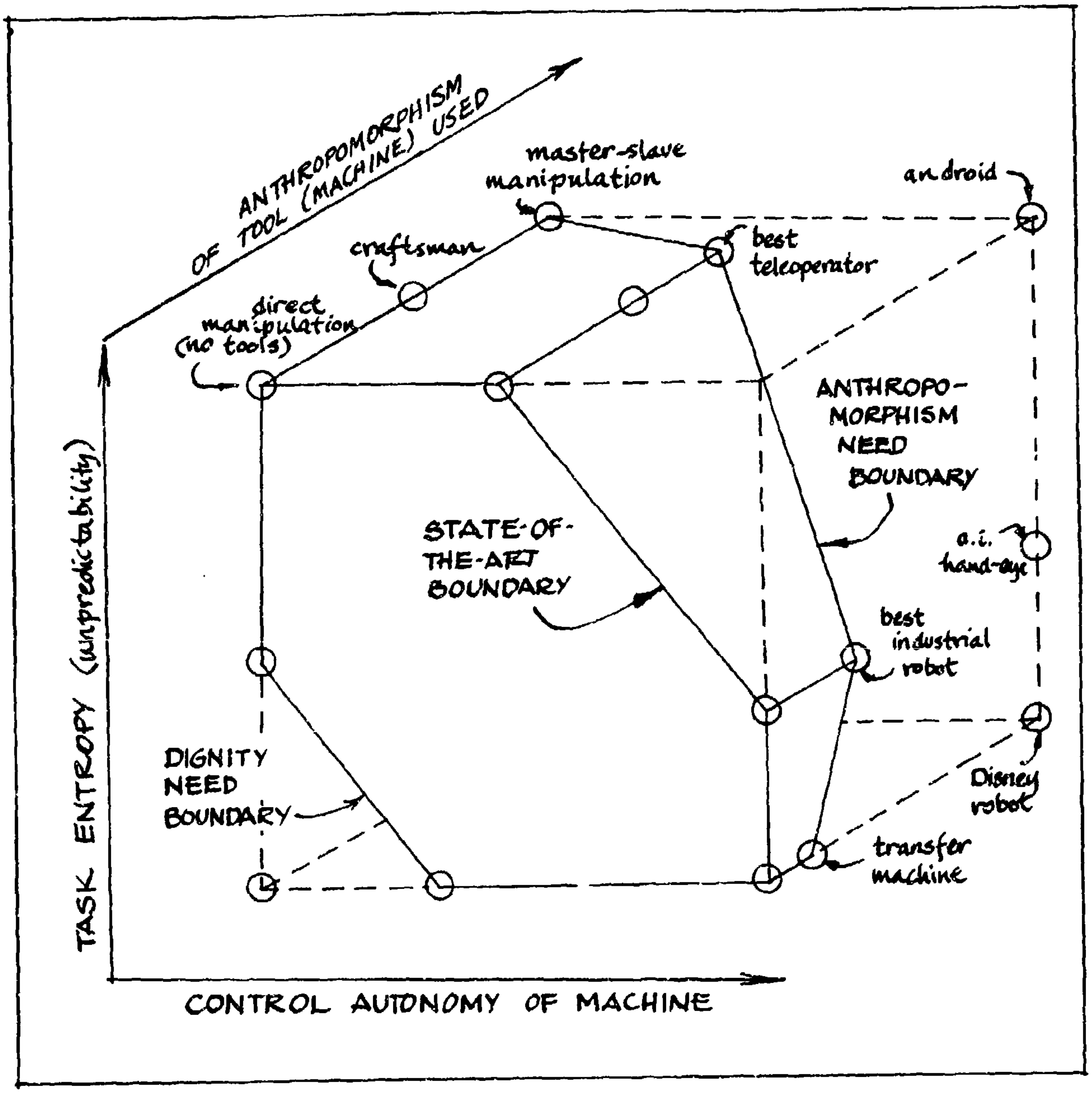


FIGURE 5.8 DOMAIN OF MAN-TOOL SYSTEMS IN WHICH ANTHROPOMORPHIC TOOL DESIGN IS USEFUL. This is an extension of Figure 4.3. Useful man-tool systems can be represented by a rectangular solid-truncated at the lower left corner by our refusal to employ people as slaves, at the upper right corner by our limits on knowledge. It is also truncated by a right-rear diagonal slice which, for good design, requires less anthropomorphism as control autonomy increases or as the task entropy decreases (task becomes more predictable).

6. CONTROL SOFTWARE FOR COMPUTER-AIDED MANIPULATION

Previous sections have discussed in general the trade-offs between human- and computer-control of teleoperation (Section 4) and the hardware necessary (Section 5). This section looks in detail at the requirements for a supervisory control language and describes several examples of existing programs. The emphasis is on human interaction with such software. We propose both a general framework and some specific principles of good user-oriented language design.

6.1 Sharing vs. Trading, Transparent vs. Apparent

One useful distinction between different application of computers is in how they are supervised by the human operator; the operator either shares or trades control with the computer. Here, to share control means that both human and computer are active at the same time. To trade control means that at one time the computer is active, at another the human is.

For example, the servomechanism of a master-slave system is a form of automation with which the operator shares control. Similarly, real-time coordinate transformations (such as resolved-motion rate-control) are an application of computer-aiding where the operator shares control. Other computer-aids which would be in simultaneous operation are sensor-conditioning, communication-channels and display-aids; they share control with the operator.

The operator trades control, for example, when switching from training to automatic execution of a recorded path. Emergency overrides either by the operator or by the computer are instances of trading control.

Any particular implementation of computer-aiding may involve both sharing and trading control. When a pilot changes the heading on an auto-pilot, he is sharing control with the guidance computer. When he resumes manual control, he is trading.

A proposed design principle. This trading/sharing distinction will be used in the next section to classify various computer-aids to manipulation. The distinction may have an important bearing on how the man-machine interface should be designed. The demands on the human operator will probably be quite different in sharing and trading.

It is proposed here that in sharing the computer control should be "transparent"; the operator should be in continuous, direct control with his work made easier by computer aiding. "Transparent" here implies that the operator "sees through" the computer control directly to the task to be done. For example, a good master-slave system with force-feedback allows the operator to identify with the remote arms and hands as though they were his own.

The demands on the operator when trading control have to do with knowing what the automatic control will do, is doing and has done (that is, he must plan, monitor and intervene). In this case, the computer should be "apparent", not transparent. That is, in planning as well as programming or training for autonomous operation, it should be apparent to the operator what the teleoperator will do (and is capable of doing). In monitoring, the teleoperator and environmental states should be apparent to the operator, especially if he needs to intervene.

There may be some difficulty with this notion of "transparent" and "apparent" computer-aiding. Are there times when shared control should become "apparent"? Yes, but probably only when control is being "traded". For example, resolved-motion rate-control "shares" control; it should normally be "transparent", that is, the operator should feel that he is in direct control of the end-effector, not worrying about what the individual joint velocities are. However, if the computer "fails" for example by

reaching joint limits or gimbal-lock, this should be "apparent" to the operator so that he can "trade" control with the computer and command individual joints directly, if necessary. If there is no need to trade control, if the computer can handle the problem, it need never become apparent to the operator.

There might be situations where transparency of shared control is not appropriate but our first guess is that this is a good general design principle. Further research and field experience may show whether or not this is so.

6.2 Examples of Shared Control

Several computer-aids to manipulation where control is shared have been demonstrated in the laboratory. In general, their intent has been to put the operator in more direct control of the task at hand without having to worry about one or more of the difficulties in communication or control; they are successful to the extent they are unobtrusive or "transparent".

Resolved Motion Rate Control is a scheme invented by Whitney (1969) and evaluated by Mullen (1973), where the computer does a real-time coordinate conversion between the operator's commands (rates in room- or hand-coordinates) and the joint rates of the manipulator. This allows the operator, for example, to command a linear extension or sweep of the end effector, without having to coordinate which arm joints to move at what velocities.

In general, this kind of computer-aided coordinate conversion would allow the operator to specify the desired end-point position or velocity and have the computer decide what combinations of component joint articulations will produce that desired result.

Auto-Indexing was suggested by D. Jelatis (1977) and implemented by Brooks (1978). If the range of the master in a master-slave manipulator cannot be as large as that of the slave (such as on a manned submersible) one possibility is to have a simple difference in scale. However, this makes small motions difficult. Another option is to allow a 1:1 correspondence but only within a small volume of the master's motion; if the operator tries to push the master outside that volume, the slave is "indexed" at a rate proportional to how hard the operator is pushing and in the appropriate direction. The result is an offset between master and slave positions, but continued master-slave control with force-feedback. If the allowed volume of master motion is set to zero this becomes a mixed mode of control where translations of the end-effector are under rate control, and orientations are under position control.

Predictor Displays are a form of computer-aiding that make control easier by presenting dynamic information to the operator which would otherwise be hard for the operator to estimate. They have been proposed as computer-aids for better human control of remote untethered submersibles (see Section 5.3 and 7.6). In a sense, the computer-aid is transparent to the operator who directly controls the position of the predictor symbol; the vehicle then "follows" the predictor.

Automatic Slaving of T.V. Camera to Arm Position has been suggested by Wernli (1978) for application on the Navy's Remote Underwater Work System. Their studies of time spent in camera positioning (for several salvage scenarios) show nearly 10% of the time is spent on camera positioning. Under computer control the camera could be positioned to always keep the manipulator hand in view, thus alleviating the operator of the necessity to move or adjust the cameras.

Active Accomodation. In attaching one part to a mating part, if alignment is not near perfect, forces may build up, the objects bind, and the desired final attachment may never succeed. This can be avoided with sufficiently sensitive force-feedback on master-slave manipulators; yet,

force-feedback to the operator may be undesirable because of communication restrictions (e.g., time-delay) or expense. If the manipulator is equipped with a suitable wrist-force strain sensor, or with tactile sensors, the computer may be programmed to make the manipulator "seek" a least-force ıth which moves the grasped part in the desired direction (Groome, 1972).

This is a form of computer-aid that the operator might share control with; the operator controls gross motions, the computer makes fine adjustments upon contact. Accomodation will also be of value to pre-programmed operations where the operator has traded control with the computer. In either case, the properly chosen accomodation scheme could be "transparent" to the operator or the program commanding the assembly sequence.

It should be noted that passive compliance (the mechanical and ser springiness) is vital in any form of manipulation. Some things would be impossible without it, for example maintaining contact with fixed objects. For specific tasks, special fixtures can be designed which have the appropriate compliance built in. For example, an ingeneous recent development called "remote centered compliance" allows a grasped but misaligned "peg" to translate and rotate about an axis displaced from the manipulator hand, and thus align itself with the "hole" while still being forced into mating (Drake, 1977; Whitney, 1978).

6.3 Examples of Traded Control: Manipulation Languages

When the operator trades control of the teleoperator to a computer, his instructions or sequence of commands to the computer could be called a language. For manipulation there have been developed two kinds of language: world-modelling and explicit (Park, 1977). World-modelling languages are high-level problem-solving experiments in artificial intelligence. They would accept commands such as "assemble the water pump". Explicit manipulation languages allow the operator (or the world-modelling program) to assemble sequences of primitive manipulator actions. They accept commands such as "CLOSE" (the jaw).

World-Modelling and Artificial Intelligence. It is possible to hypothesize an intelligent teleoperator with enough autonomy to be called a robot. Many of the components are under active development, in fact much of the artificial intelligence research has used manipulation as an example problem (Winston, 1977). Natural language understanding by computer was demonstrated by Winograd for the restricted case of arranging blocks, pyramids and boxes (the "Blocks World"). Scene analysis from the Blocks World was solved by Waltz by exploiting the constraints imposed by real polyhedra on their line drawings. Some of the earliest work on problem solving was demonstrated at SRI with a general problem solver (GPS) called STRIPS.

More recently, the focus of problem solving research and the planning of manipulation has shifted to the representation of knowledge for particular problem domains. Two alternative kinds of knowledge are identifiable: 1) knowledge about the actions possible in that domain (PROCEDURAL) and 2) knowledge about the state of the domain (DECLARATIVE). A currently popular structure which combines these is Minsky's Frame Theory.

A successful embodiment of the Frame Theory is NOAH (Nets of Action Hierarchies), an integrated problem solving and execution monitoring system intended to serve within a larger computer system called the Computer-Based Consultant (Sacerdoti, 1977). NOAH's knowledge of the actions in its world is encoded in a "procedural network". Two phases of computer planning are used: first automatic expansion of general procedures to successively more detailed levels; then an over-all look to ensure that the local expansion makes global sense.

Much of this work in artificial intelligence has been aimed at understanding the general problems of intelligence, not at accomplishing practical manipulation. For example, NOAH has planned the assembly of a water pump but assumed a human as a manipulator. Other current world-modelling languages which are specifically designed for the planning of manipulation are AL at Stanford University (Goldman, 1977), LAMA at M.I.T. (Lozano-Perez, 1977), and AUTOPASS at I.B.M. These are all sophisticated programs running on large computers. Their first practical contribution will probably be in planning for industrial automation of mechanical assembly. They are a

long way from being on-board controllers for teleoperators in uncertain environments.

Other planning programs. Several other experimental computer aids to manipulation fit into the class of world-modelling programs but at a somewhat less ambitious level than artificial intelligence.

Whitney (1969) showed how to represent manipulation problems with a state-space. Solutions are then found with search techniques in this state-space. He found that for simple tasks with few objects, optimal paths are easy to find, but that for realistic six degree-of-freedom, dynamic objects and manipulators, the options are simply too numerous for an exhaustive search in a realistic time.

Hardin (1970) proposed some planning heuristics at a somewhat higher level where tasks were organized in an AND-Tree which would be expanded to detail actions and trimmed by a critic which avoids duplications and checks for loops. (This is very similar to Sacerdoti's procedural nets.)

Freedy (1971) and Albus (1973) have both designed learning systems which observe the human operator's control of the arm and look for patterns of motion which can be automatically executed. The explicit command of arm motion appears to be a more practical alternative.

Explicit Arm Languages. Today's general purpose industrial robots have very simple point-to-point programs which are usually programmed by moving the manipulator under manual control to successive points and recording them. This record/playback mode will probably be one of the first useful computer-control modes for undersea teleoperators. Some useful parallels in programming details might be worth investigating. We give no further details here.

Probably the first computer controlled manipulator which could respond purposefully to its environment was MH1 programmed by Ernst (1961). His

BBP-1 program could be used by the human operator sitting at a keyboard, for instance to build small structures or to search for and collect blocks, by calling on a range of simple and complex subroutines. The manipulator jaw was equipped with a variety of touch sensors and a simple optical proximity sensor.

A rather complete review of computer-controlled manipulation has been compiled by Bejczy (1973) so no further history will be given here. What is of concern are the details of user interaction with such computer-controlled manipulators. Some further examples will be given.

<u>The C.S. Draper Laboratory</u> (1977) has an arm programming language which allows the programmer to write a sequence of moves and tool actions. The computer then walks the arm through the sequence, pausing when an unspecified arm position is encountered, and waits for the programmer to move the arm there manually and push a "record" button. A program sample is shown here:

```
MC EF  COLLETPICKUP AS MOVE(1,UC,2,3,3,CG)
         MOVE(1,LC,7)

MCDEF  COLLETINSERT AS MOVE(4,UC,5,6,6,CR)
         MOVE(4,LC,1Ø)

         ATTACH TOOL
         LOCK
         COLLET RELEASE
[NUT]    COLLETPICKUP
         COLLETINSERT
[LOCKWASHER]  COLLETPICKUP
         COLLETINSERT
[FANSPACER]  COLLETPICKUP
         COLLETINSERT
[BEARINGSPACER]  COLLETPICKUP
         COLLETINSERT
         CLEAR CR
         CLEAR LC
```

The arm velocity goes to zero only at the beginning and end of a MOVE sequence. 1,2,3 label arm positions to be later specified. UC, CG, LC are tool motions (unlock compliance, colletgrip, lock compliance), which can occur while the arm is moving. MCDEF defines a "macro". Positions can be defined locally (labels 1-19) within a move, or globally (20-49).

The CSDL system of teaching by showing followed by record playback is similar to conventional industrial robots. A significant difference is that the program sequence can be edited without losing any taught data and positions which must be returned to several times within a program can be taught once and referenced by number.

SRI International is developing a slightly more sophisticated user language for control of industrial robots (Rosen, 1977). It is a FORTRAN-like language with libraries of user-written subroutines. They currently have over 160 such routines. An example of a user-language application program is given here:

```
          COMMON
          DATA NTIMES=10
          INTEGER JUNK,                     ! RECEIVES A TYPED-IN CHARACTER
                P1=2,P2=4                   ! NUMBERS OF POSITION TRANSFORMS
          END

          PROGRAM P$SAMPLE                  ! MAIN PROGRAM
          TYPEL  "SAMPLE PROGRAM"           ! PRINT THE TITLE
          ISETZ COUNT
          INIARM                            ! START UP ARM
          JOYON 0                           ! TURN ON JOYSTICKS
          INCHRV JUNK                       ! WAIT FOR A TYPE-IN
          TCOPY (P1,-#26)                   ! RECORD 1st POSITION
          INCHRV JUNK                       ! WAIT AGAIN
          TCOPY (P2,-#26)                   ! RECORD SECOND POSITION
L$LOOP    S$WAVE                            ! CALL SUBROUTINE 'WAVE'
          IPLUS ( COUNT, COUNT, 1)          ! DO IT "NTIMES"
          IFLSS ( COUNT, NTIMES,L$LOOP)     ! IF (COUNT.LT.NTIMES)
          STOP                                        GO TO L$LOOP
          END
```

(continued on next page)

```
! THIS SUBROUTINE WAVES THE ARM BACK AND FORTH BETWEEN
! POSITIONS P1 and P2 ...

   SUBROUTINE S$WAVE
   MOVETO P1                        ! START ARM MOVING TO P1
   WAITTC                           ! WAIT TIL IT GETS THERE
   MOVETO P2                        ! THEN MOVE IT TO P2
   WAITTC                           ! WAIT TIL IT GETS THERE
   RETURN                           ! RETURN TO CALLER
   END
```

INCHRV is used to wait for the operator to move the arm manually and then type in any character. Then TCOPY records the current arm position. Note the limited arithmetic capabilities (ISETZ, IPLUS) and the ability to test and branch (IFLSS).

Rosen et al. (1977) have identified user interaction as an important area where improvement can be made. Some improvements planned are: hot editing (where a program can be modified while the arm is executing it), immediate execution (where the arm executes a statement as soon as it is typed) and interactive execution (such as inserting temporary break-points where control is transferred to the operator).

VAL is probably the most sophisticated explicit programming language available commercially (Unimation, 1977). It allows positions to be trained by manually moving the manipulator or specified in terms of room coordinates or joint coordinates, or hand coordinates. It operates in real-time, simultaneously issuing manipulator commands and interacting with a human operator or other interactive controller. This permits on-line program generation and modification ("immediate execution" and "hot editing").

MANTRAN (Barber, 1967) was an early language designed especially for interactive supervisory control of a teleoperator. The manipulator was equipped with FRONT, LEFT and BOTTOM touch sensors and the language allowed branching on the basis of this information. For example, here is a program that moves the arm down, forward and left until it touches the bottom-front-left

corner of its work space. If it moves 2000 steps before touching it stops and types "help".

```
              MOVE TO CORNER

ST.1.  MOVE LEFT 2000 DOWN 2000 FORWARD 2000.
     UNTIL A.) TOUCH LEFT
           B.) TOUCH FRONT
           C.) TOUCH BOTTOM
IF MOVE CONDITION SATISFIED,  HELP
     IF A.)  DO 2
     IF B.)  DO 5
     IF C.)  DO 7

ST. 2.MOVE DOWN 2000 FORWARD 2000.
     UNTIL A.) TOUCH FRONT
           B.)  TOUCH BOTTOM
IF MOVE CONDITION SATISFIED,  HELP
     IF A.) DO 3
     IF B.) DO 4

ST. 3.  MOVE DOWN 2000.
     UNTIL A.)  TOUCH BOTTOM
IF MOVE CONDITION SATIFIED, HELP
     IF A.) DO 8

ST. 4. MOVE FOWARD 2000.
     UNTIL A.)  TOUCH FRONT
IF MOVE CONDITION SATISFIED,  HELP
     IF A.)  DO 8

STAT. 5.  MOVE LEFT 2000 DOWN 2000.
     UNTIL A.)  TOUCH LEFT
           B.)  TOUCH BOTTOM
IF MOVE CONDITION SATISFIED, HELP
     IF A.)  DO 3
     IF B.)  DO 6

STAT. 6.  MOVE LEFT 2000.
     UNTIL A.)  TOUCH LEFT
IF MOVE CONDITION SATISFIED, HELP
     IF A.)  DO 8

STAT. 7.  MOVE FORWARD 2000 LEFT 2000.
     UNTIL A.)  TOUCH FRONT
           B.)  TOUCH LEFT
IF MOVE CONDITION SATISFIED, HELP
     IF A.)  DO 6
     IF B.)  DO 4

STAT. 8.  OPEN 1000*
```



```
STAT. 9.  GO TO END
```

There were several limitations which MANTRAN revealed. There was no analogic training mode, all the commands had to be typed in at a keyboard. This made direction and position specification difficult and "unnatural". Another difficulty had to do with keeping track of the complex structure of the program. The sample above is a good example of how, through awkward syntax, the multiple branching makes the program difficult to read, understand and debug.

Other languages for supervisory control of teleoperators have been written at SRI (J. Hill, 1973), at J.P.L. (Bejczy, 1976) and at Perceptronics, Inc. (Shaket, 1977). They have all featured the ability either to control the manipulator directly with some form of manual control or to have the computer execute a sequence of manipulator commands, and transfer control back to the operator. Some of the results are discussed in Section 7. A program recently developed at M.I.T. is described in Section 6.6.

6.4 Elements of a Manipulation Language

In an attempt to organize these different programming languages, common basic elements can be identified.

ACTIONS. Most basic are the primitive manipulator motions, usually position commands or velocities, either specified absolutely or as increments either in joint coordinates or some more convenient frame.

SUBROUTINES/PROCEDURES. The next most basic programming feature is to invoke sequences of actions by name or number. This is the most powerful simplifying feature to the human operator. Libraries of manipulation routines allow complex operations to be easily and quickly programmed by combining pre-defined sub-tasks.

FLOW-CONTROL is usually accomplished with tests and branching to labelled statements. The particular form of conditionals used determines the structure of the program. For example, GOTO has been recently condemned because it leads to complicated program structures difficult to understand and debug (Alagic, 1978). The tests might be on the status of sensors

(e.g., touch) or on variables internal to the program (e.g., counters).

VARIABLES/OPERATIONS. The simplest variable is a named position of the arm which can be returned to. Arm motions, or sensor data, when properly represented, can be operated on in various coordinate-frames. Most languages also require some form of declaration and allow assignment of values to variables.

INTERACTION. Finally there must be some form of interaction with the operator or programmer. This will be especially important to teleoperators where the human supervisor will be available as monitor, ready to intervene. Particularly valuable forms of interaction are teaching of positions through a convenient form of manual control, on-line editing of programs (immediate execution and hot editing) and, of course, convenient means for trading direct control of the manipulator smoothly from human to computer and back.

6.5 Principles of Interaction

It seems appropriate to discuss several design trade-offs which raise questions of human preference. It may eventually be possible to formulate some human factors principles for supervisory control.

Natural vs. Constrained Language. Ferrell (1973) has presented this issue well with a simple experiment. The question is, how constrained should the language be? Should the computer only respond to a small set of commands or should it allow use of unconstrained, natural language? The point that Ferrell makes is that for simple constrained tasks natural language is inefficient; with a special purpose vocabulary suited to the task the human supervisor is quicker at generating sufficient instructions. That is, independent of how powerful or autonomous the computer/manipulator is, the human operator is better able to generate commands if the vocabulary is suitably constrained. Probably some subset of natural language is the appropriate compromise.

For example, the VERB-NOUN syntax is a "natural" sequence that has been used to structure operator commands. Most computer assembly language is written this way (ADD B; STO C; CMP D; JMP E). The Apollo guidance computer was programmed this way with numbers (15, 32; 03, 71; ...). Perceptronics' latest keyboard for arm control (Shaket, 1977) is organized around this VERB-NOUN syntax (GOTO 5 DO; INC X (15) DO), adding modifiers (adverbs) and terminators (DO represents the end of a command).

<u>Well-Structured Programs</u>. Another issue related to the natural vs. constrained trade-off has to do with the selection of control structures (e.g., IF [condition] GOTO [label]). By properly constraining the choice it may be possible to avoid programs which are impossibly complex and difficult to understand. The current interest in "structured programming" was notivated by a concern for the abilities and limitations of human programmers.

<u>Analogic vs. Symbolic</u>. This issue is discussed in Section 5 in regard to the hardware for command inputs. It is also appropriate here in the discussion of software, because any language for manipulation naturally has analogic descriptions (of actions, forces, directions, orientations). Where the human operator is required to make such specifications the appropriate communication mode ought to be used. For example, most industrial robots have a training mode where rather than specifying positions on a keyboard as numbers (symbolic) the operator drives the robot manually to the desired position (analogic). On the other hand, where precision is required the symbolic mode might be most appropriate, for example, in programming numerically controlled machine tools. Yet even for numerically controlled tools, there are aspects of the overall planning and verification of tool motion where the analogic and pictorial mode is more appropriate (Gossard, 1975).

The appropriate form of command hardware may depend on what level in a hierarchy of task abstraction the communication takes place. Figure 6.1 illustrates these trade-offs. Figure 6.2 elaborates.

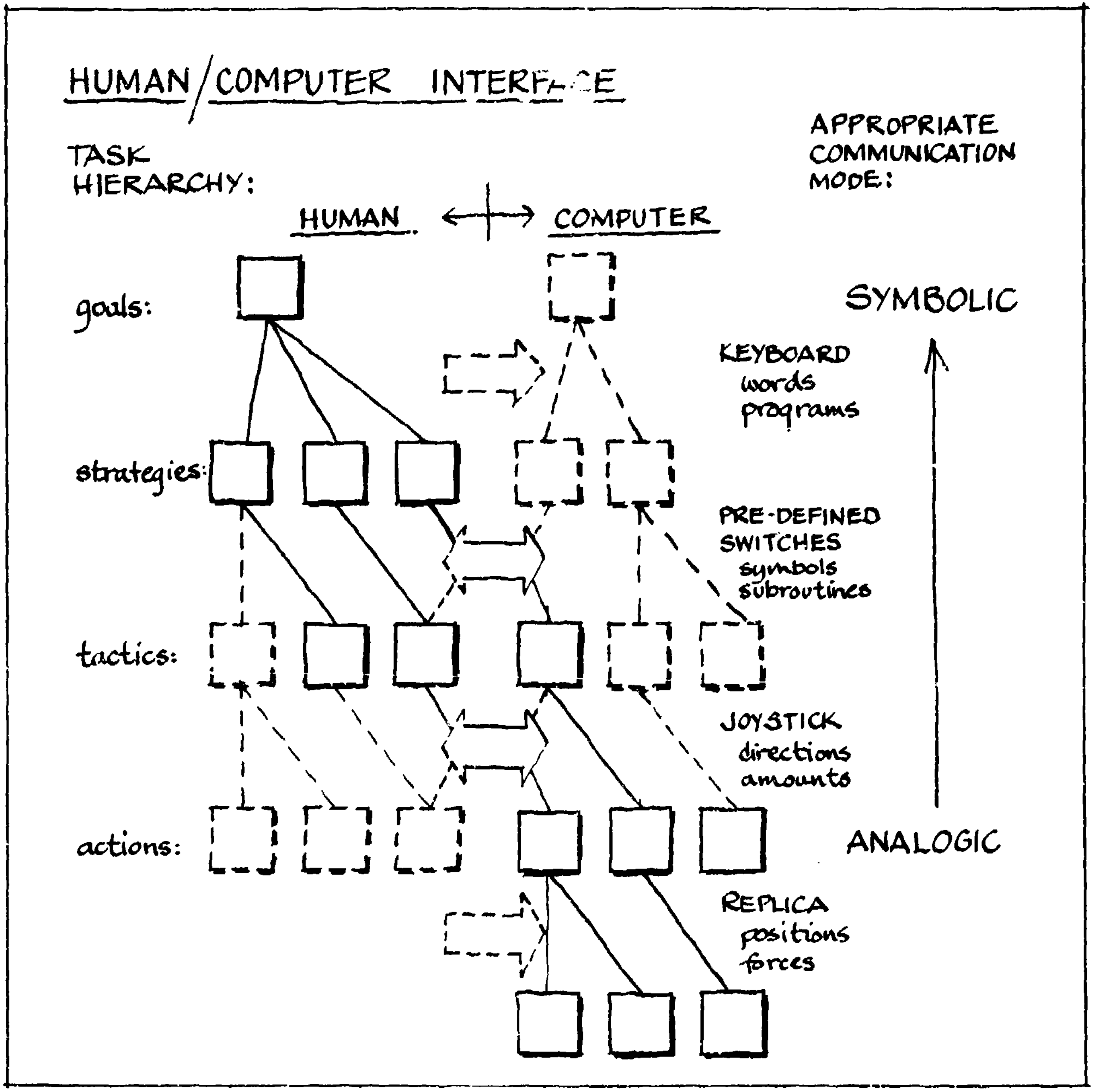


FIGURE 6.1 COMMAND HARDWARE FOR COMPUTER-AIDED MANIPULATION can be organized on a task hierarchy with different communication modes appropriate at different levels. At the highest level are the symbolic commands (e.g., words, programs, labelled positions and subroutines); at the lowest level are the analogic commands (e.g., directions, amounts, positions and forces).

Allowing for a range of communication modes has been proposed as an evolutionary strategy for design of supervisory control (Verplank, 1967). The symbolic/analogic dichotomy may have to do with the alternative modes of human knowing and thinking (Verplank, 1976).

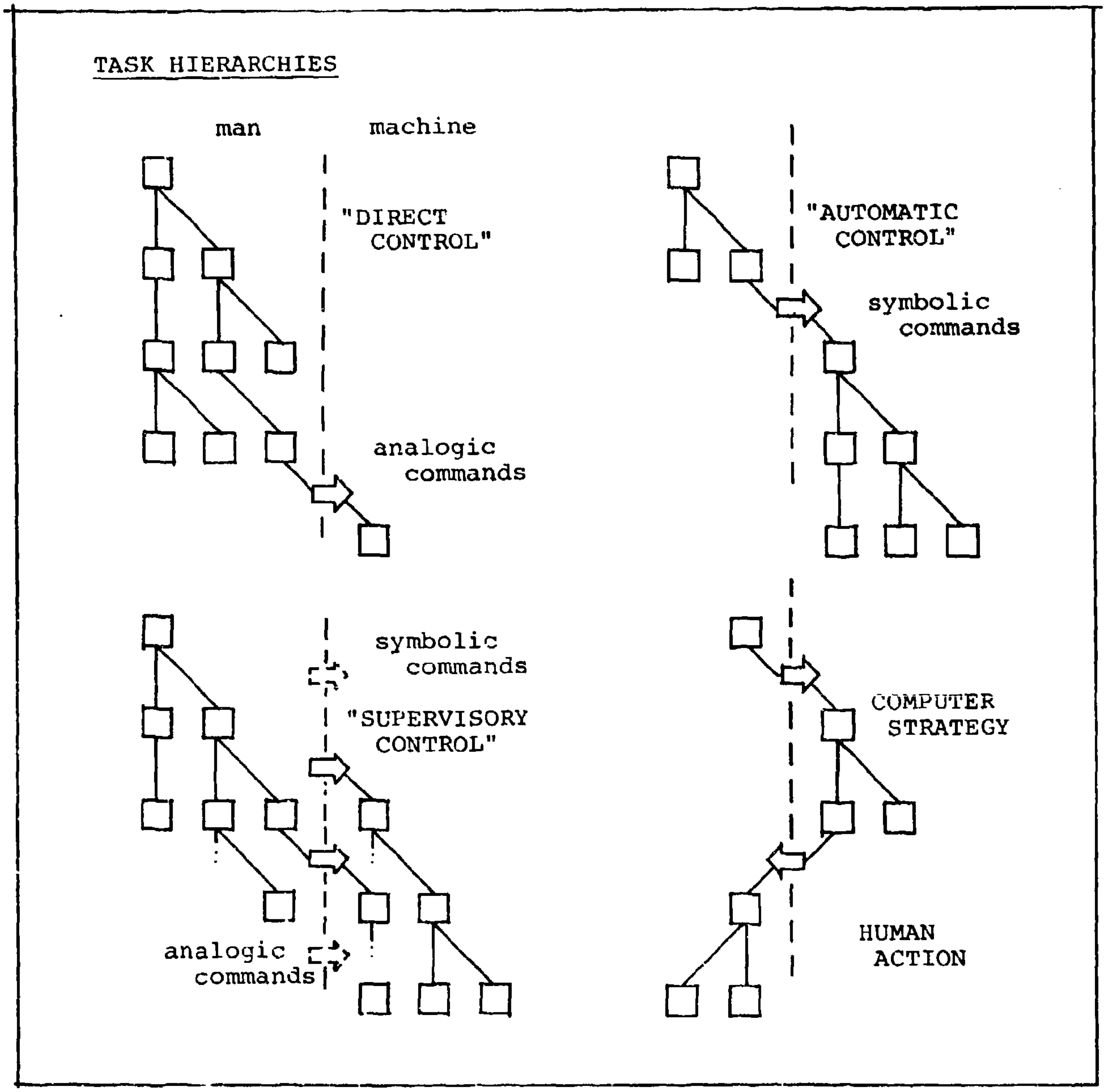


FIGURE 6.2 ALTERNATIVE TASK HIERARCHIES show the need for alternative communication modes.

With increased automation, the communication becomes increasingly symbolic (higher on the hierarchy). Properly designed supervisory control should allow a range of communication modes (analogic to symbolic) for different levels of automation.

Note also that the commands may sometimes go from computer to human as, for example, with the computer keeping track of a search strategy or assembly sequence.

Other human factors issues have already been discussed. For example, one idea is that for sharing control the computer should be transparent; for trading control it should be apparent. The coding of symbolic commands is another issue. For example, should special purpose keyboards or general purpose keyboards be used, single keystrokes or multiple keystrokes? Is a SEND, DO, or CARRIAGE RETURN necessary? Is a back-space or delete possible?

There are many principles which can be transferred from the general domain of computer programming. For example, methods of dealing with both novice and expert programmers: HELP commands, menus and error messages which can be either succinct or elaborate , optional abbreviation of both feedback and commands.

Possibly the most important general principle at this early stage in the development of supervisory control for teleoperators is flexibility. As experience is gained, as new sensors and actuators are developed, the trade-off between human and computer control will shift. A properly designed supervisory control language which allows communication in a variety of levels and modes will be ready for adaptation and evolution.

6.6 SUPERMAN: A System for Supervisory Manipulation

A brief description of a thesis by T.L. Brooks in progress at the Man-Machine Systems Lab at MIT is given on the following pages as an example of a supervisory manipulator system. This system is called SUPERMAN. Figure 6.3 shows the general relationships between the multiple inputs (keyboard, dedicated symbolic keys, and analogic inputs), the computer states (STANDBY, DEFINE, EDIT, EXECUTE, and TAKEOVER) and the control modes (RATE, MIXED MASTER/SLAVE AND RATE, MASTER/SLAVE, and COMPUTER control).

STANDBY State - When the computer is in this state, control resides with the main program and the operator. By pressing the proper button on the control console the user can enter a particular manual control mode or another computer state (see Figure 6.4).

Manual Control Mode - A manual control mode is the method through which the user analogically interacts with the arms. A control mode is independent of the state, for example, the control mode might be MASTER/SLAVE while the state is EDIT. There are three kinds of modes:

1) RATE - The individual degrees of freedom are controlled through rate commands by switches on the control console and a potentiometer for rate adjustment. Both rate and resolved-motion rate are available.
2) MIXED MASTER/SLAVE AND RATE - The master acts as a spring-loaded joystick in the X, Y and Z axes, giving rate commands to the X, Y and Z axes of the slave proportional to displacement of the master. (The rate of the slave arm is then reflected in the force-feedback level which the operator feels in the master.) Both rate and resolved-motion rate control are available. The remaining degrees of freedom, the left and right elevation, the azimuth and the end-effector are controlled in a master-slave mode.

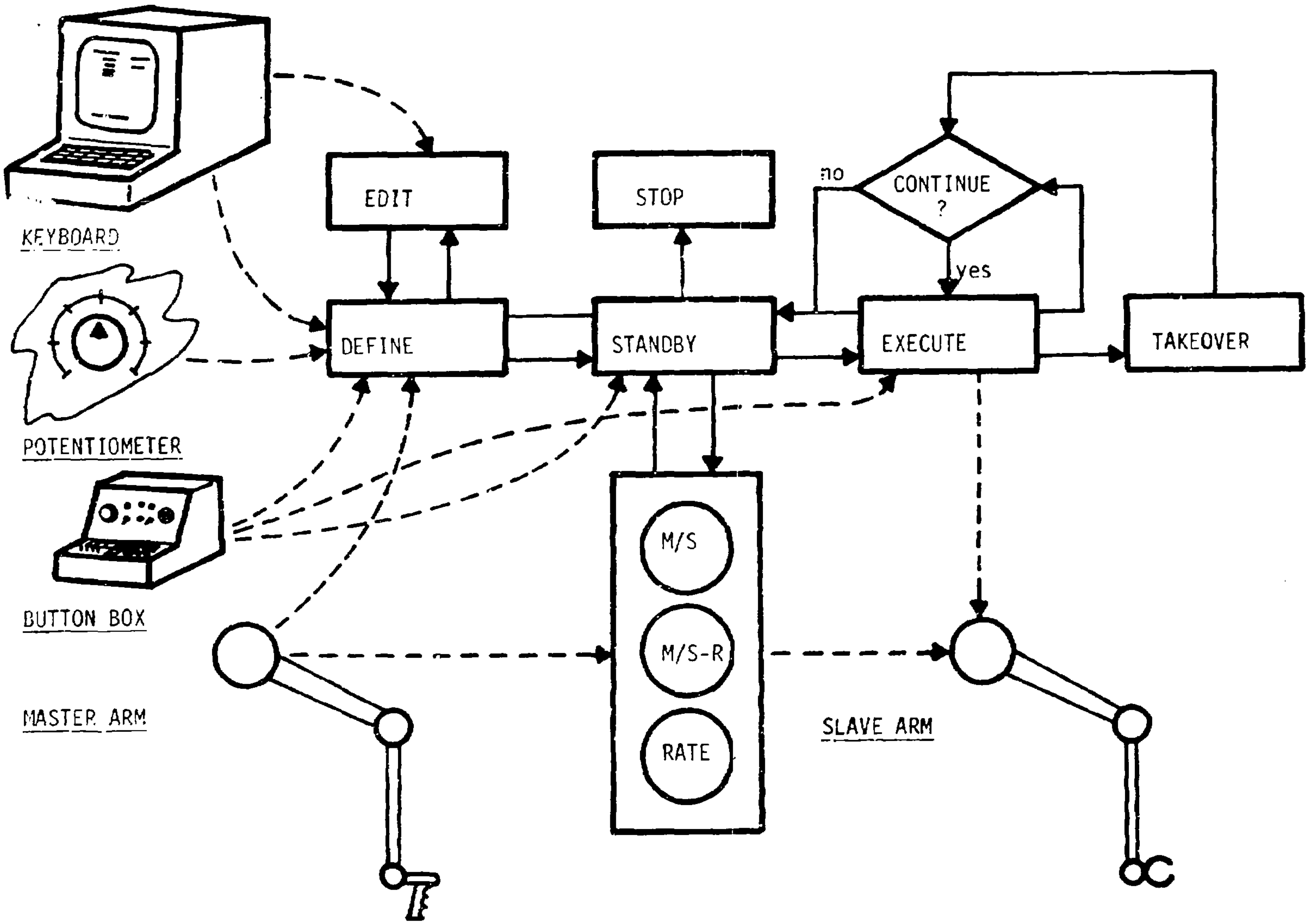


FIGURE 6.3 Computer states and control modes for SUPERMAN (Brooks, 1978).

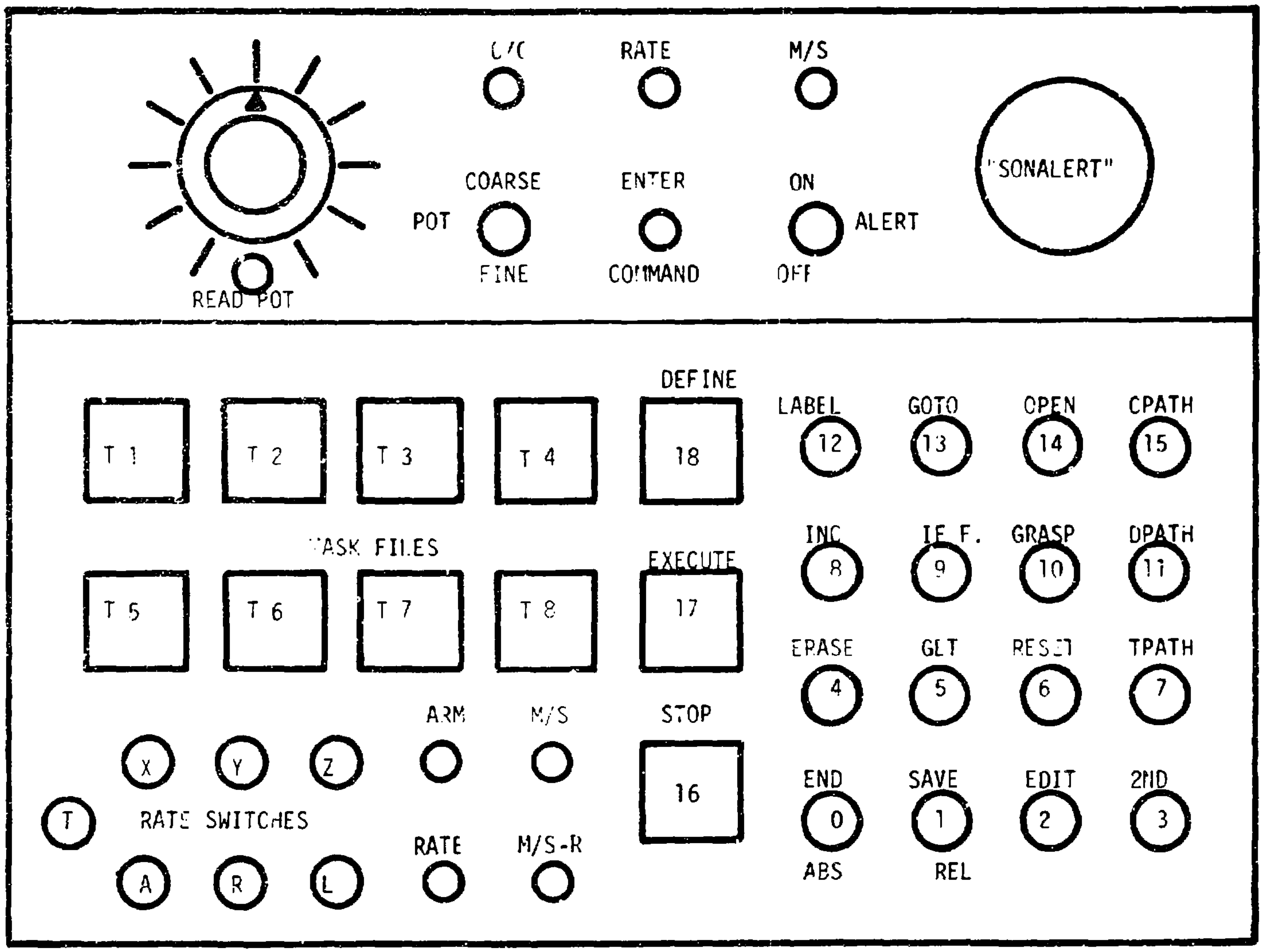


FIGURE 6.4 SUPERMAN Button Box (Brooks, 1978)

3) MASTER/SLAVE - The slave arm is driven to duplicate in position the action of the master. Any force felt by the slave is reflected to the master giving the operator force feedback (i.e., proportional to position disparity between master and slave).

DEFINE - DEFINE is the primary state through which the operator enters a string of commands to be executed. Commands are entered by pressing specially dedicated buttons for each function. All of the buttons used in the DEFINE state have dual functions (see Figure 6.4, dual function buttons are 0-15).

EXECUTE State - As the title implies, the string of commands is executed through this state. During the execution of the command register, if the operator desires to take control, there are two methods available. The operator can take immec .te control: (1) by pulling on the appropriate control stick (i.e., the MASTER in the case of master-slave or MIXEC MASTER/SLAVE AND RATE modes or the rate switches in the RATE mode), or (2) by pressing the STOP button (all action ceases after the STOP button has been pressed until the operator signals for continuation or return to STANDBY). The operator can execute a string of commands which have been saved as a task file by pressing one of the lighted TASK FILE buttons. The operator also has the option of executing the current command register by pressing the EXECUTE button. This allows the operator to define a string of commands and immediately execute them to determine if any modifications are necessary. After the operator is sure the command string performs the desired function correctly that function can then be saved as a task file or a named file.

TAKEOVER State - TAKEOVER is a transition state between control modes, i.e., from computer control to the control mode in effect before the EXECUTE command. Special problems result during this state due to the mismatch between the master and the slave at the time of the takeover. The diamond in Figure 6.3 signifies that after the mismatch has been dissolved, the operator has the option of moving into the STANDBY state or continuing the EXECUTION state.

The dedicated-button commands associated with DEFINE are:

BUTTON Number	Command
0	END Final command used to signal completion of DEFINE state.
1	SAVE Used to save the command register on the disk as either a task file or a named file. A task file can be recalled only by one of eight buttons in the STANDBY state, whereas a named file is saved under a user-designated title and can only be recalled by the same name through the GET button (5) in the DEFINE state.
2	EDIT The EDIT command allows the user to modify the command register. The following options are available through the keyboard after entering the EDIT state; a) CHANGE A LINE b) INSERT A LINE c) DUPLICATE A LINE d) DELETE A LINE e) LIST COMMAND REGISTER f) RETURN TO DEFINE
3	2ND Used to enter the second function of dual command keys. The first function of each key is printed in black letters above the button. The second function is written below the button in gold letters. To enter a second function command, press the 2ND key and then the desired second command.
4	ERASE LAST LINE [ERASE] Used to erase the last entry in the command register.
5	GET Used to retrieve a named command file from the disk. GET asks for the name of the command file to be recalled and then locates the file, reads it into the command register (and returns to DEFINE state).
6	RESET Used to initialize the necessary internal variables and the command register to zero.

7 THROUGH PATH [TPATH]

Records the present position of the arm for use in EXECUTE as a through point. (A through point is a position which the operator desires the arm to move through without stopping, i.e. non-zero velocity point.)

8 INCREMENT [DOF] (XXXX)

Makes an incremental motion in the desired degree of freedom by a selected value. The user enters the INCREMENT command, then the degree of freedom [DOF], adjusts the desired increment (XXXX) through the potentiometer and presses the READ POT VALUE button directly beneath the potentiometer.

9 IF [DOF] FORCE.GT. (XXXX)
EXECUTE NEXT COMMAND

If the force level in the desired degree of freedom [DOF] is greater than the level set by the operator (XXXX) the following command is executed. If the force level is less than the level set by the operator, the command immediately following the IF FORCE.GT. statement is skipped during execution. The user enters the IF FORCE.GT. command, then the desired degree of freedom, adjusts the force level through the potentiometer.

10 GRASP WITH FORCE (XXXX) [GRASP]

The user enters the GRASP command and adjusts the force level through the potentiometer.

11 DISCRETE PATH [DPATH]

Records the present position of the arm for use in EXECUTE as a stopping point. During execution, the slave arm is moved from its current position to the recorded position with zero final velocity.

12 LABEL [N]

Labels a position in the command register which can be returned to through a GOTO command. The user presses the LABEL button and then the number [N] of the desired label.

13 GOTO [N]

GOTO is a conditional command which moves to label [N] unless the operator signals during execution to change the branch to [M] by pressing a different button. To enter the command the operator presses the GOTO button and then the number [N] of the label to which GOTO should branch.

14 OPEN

Open jaws.

15 CONTINUOUS PATH [CPATH]

Records the position of the master manipulator every 0.1 second for use in EXECUTE. A continuous path is achieved by interpolating between the recorded positions.

2ND - 0 ABSOLUTE

Informs the execution compiler that the command register is to be executed exactly as recorded (see RELATIVE). The user enters the absolute command by pressing the 2ND button [#4] and then the ABSOLUTE button [#0].

2ND - 1 RELATIVE

Informs the execution compiler that the positions in the command register are to keep the same relative displacement with respect to each other, but are to be transformed so that the first position following the RELATIVE command corresponds to the position of the slave at the time of execution. A RELATIVE command can be cancelled by an ABSOLUTE command, with the result that only the positions between the RELATIVE and ABSOLUTE commands are transformed. The user presses the 2ND button [#4] and then the RELATIVE button [#1] to enter the command in the register.

2ND - 2 through 2ND - 15 not assigned.

As an example program consider a string of commands to take a nut off of a bolt and put it in a box. This program can be broken down into two major sections; one removes the nut and the other places it in the box. Since the user would prefer one nut removal program to be used for all nuts regardless of the orientation of the nut, a RELATIVE command should obviously be the first command in the register (the RELATIVE command and all of the following commands listed above are used under DEFINE). The entire command register for the nut removal program would be as follows. The following general format will be followed throughout this example:

[BUTTON PUSH]

(POT READINGS)

"KEYBOARD COMMANDS"

COMPUTER REPLIES.

1	[RELATIVE]	
2	[LABEL] [1]	
3	[DPATH]	Place the slave on a nut and record that position by pressing the DPATH button.
4	[GRASP] (200)	
5	[DPATH]	Turn the end effector 180° and record the position.
6	[INCREMENT] [Y] (300)	Increment the slave by 300 counts in the direction that would pull the nut off.
7	[IF FORCE.GT.] [Y] (100)	If the force is greater than 100 in the Y direction, the nut is still on the bolt, therefore execute the next command.
8	[GOTO] [2]	
9	[GOTO] [3]	If the force had been less than 100 in the Y direction, the nut is free and this command would be executed.
10	[LABEL] [2]	
11	[INCREMENT] [Y] (-300)	Return the arm to position before incrementing in #6.
12	[OPEN]	Release the nut.
13	[GOTO] [1]	Return to LABEL 1 and continue turning the nut.
14	[LABEL] [3]	End of the first part of task - nut is off.
	[SAVE] "NUT-OFF"	Save command register as the named file "NUT-OFF" (typed in at the keyboard).

The second part of the task requires the manipulator to place the nut in a box. The entire command register for the program to put the nut in the box would be as follows:

1	[ABSOLUTE]	The box would always be in the same place.
2	[TPATH]	Move the slave to a position just over and above the outside edge of the box and record this position by pressing the TPATH button.
3	[DPATH]	Move the slave to a position over the center of the box and record the position.
4	[OPEN]	
5	[TPATH]	Enter same position as in #2 by duplicating line 2.
	[SAVE] "NUT-IN-BOX"	

At this point the operator could call either program and execute it. The NUT-OFF program would simply take the nut off and return control to the operator as soon as the nut was free. But the present status of each file (i.e. a named file) requires that the operator type in each name to obtain the file to execute it. If the operator performs the following commands the file will be saved as a task file which is immediately executed at the touch of a button:

[GET] "NUT-OFF"

[GET] "NUT-IN-BOX"

The computer will reply by stringing the two files together as one file. Then enter:

[SAVE] "TASK-FILE"

and press the button which will retrieve the file (e.g., button #1). To remove a nut and put it in the box the operator simply presses the same button, the execution compiler transforms the first half of the register relative to the position of the slave at the instant the button is pressed and then executes the program. After the nut is removed and placed in the box the slave returns to the operator's position and the computer relinquishes control.

7. HUMAN OPERATOR PERFORMANCE

This section reviews data comparing the performance of various control modes of teleoperation and presents some of the attempts to model and predict performance. The focus is on manipulation and not on vehicle control and navigation.

Proper evaluation of a manipulator system must include: 1) the tasks which can be accomplished; 2) the quality (e.g., speed and accuracy) with which they are performed; and 3) the "costs" of achieving that performance. Most of the data available is from laboratory experiments on a limited set of tasks and usually completion time is the only measure of performance reported.

7.1 Performance Measurement

A recent collection of approaches to the performance evaluation of robots and manipulators was made by the National Bureau of Standards (Sheridan, 1976). Much of what is discussed there is appropriate to our concern here with teleoperator system performance.

The manipulator itself will be characterized by a variety of objective mechanical measures such as reach, work-volume, strength, slew rate, number of degrees-of-freedom, range of motion of each joint, etc. It is much more difficult to evaluate system performance which includes the human operator and his various displays and controls. The most direct method is to measure performance on a series of tasks. The tasks, as discussed in Section 3 of this report, may span a range from complete, "real-world" tasks representative of what the teleoperator may eventually face to simple abstract tasks which measure some detail of performance capability.

Physical Measures of Task Performance

Popular measures are:

Time: This is by far the most commonly used measure. It is easy to obtain and directly meaningful (i.e., correlates with operating costs).

Accuracy: Some tasks require a certain threshold accuracy ("GO/NOGO"). Others allow variable accuracy; if this is the case the accuracy achieved should also be measured and reported.

Errors: Error rate might be the most significant difference between two systems. Here, error is taken as inadvertent contact or direction reversals, and is distinguished from accuracy.

Force/Power: Use of these variables as performance measures may make some subtle comparisons possible. Peak force levels may determine maintenance needs. Energy usage may be more important for some systems than for others (e.g., untethered vs. tethered). Force-feedback can help the operator minimize manipulation forces; there should then be less "self-damage" in addition to allowing better cooperation between the vehicle and the arm, or between two arms.

Subjective Measures of Task Performance

Much of the actual teleoperator design will be done with subjective evaluation of alternative control schemes. Little attempt has been made to collect or organize these opinions. Some attempt to devise verbal scales capturing hard-to-quantify aspects of performance may be fruitful in the design of better teleoperators. Some of these attributes are: naturalness, feel, unobtrusiveness, compliance, dexterity, programming ease, flexibility, stability. Multi-dimensional scaling of observer judgements might reveal which of these attributes belong on the same or different perceptual dimensions. Such analysis might reveal a simple set of standard verbal rating scales, or at least the dominant attributes in subjective assessment or perhaps the need to re-educate the observers making the subjective judgements.

For example, we might develop a "really there" index which evaluates the operator's direct sensing of the remote task and his identification with the remote hands as his own. Other indices might include: "interface transparency", "responsiveness and controllability", "sustained work", "graceful fail", etc.

7.2 Human Performance in Laboratory vs. At-sea Situations

Most of the work discussed below was performed using laboratory manipulators, for reasons of economics and ability to control key variables. Hence the remainder of section 7 is organized on the basis of these key variables and their effects.

When real mission hardware is developed it is certainly desirable to evaluate it under semi-laboratory conditions, both to test the predictions of previous controlled experimental research and to predict at-sea performance.

An example is provided by a recent evaluation of the Navy's Work Systems Package (Bertsche et al, 1978), described in section 5. These tests utilized a variety of task scenarios done both in the laboratory and at sea: cutting openings in sheet metal structures, removing lightweight objects through the cut hole, attaching salvage padeyes with drill-tap-bolt fasteners, drilling bolt holes and attaching salvage padeye plates with multiple bolts, rigging a recovery cable, operating valves, identifying and recovering various objects.

Associated performance measurements were also done on fourteen component laboratory tasks which "collectively utilize a representative sample of all the tool suites replicated". These were: sample retrieval, acquire tool, replace tool, acquire bit, replace bit, cut rope sample, cut cable sample, brushing, hooking, valve turning, unbolting, sawing. drilling, tapping. Each of these in turn was subdivided into "behavioral actions" (travel, alignment, and tool use), "therblig" elements such as those discussed in section 3, the smallest elements for which time data were taken. Four operators performed various of the tasks and subtasks under both direct and video viewing. A major finding from these tests was that operator experience was the key factor in coping with degraded viewing conditions.

The experimenters claim a valid prediction of at-sea performance times from laboratory performance on comparable scenarios. Their results also

suggest the practical advantages of having a computer perform routine tool changing tasks, the motions for which are predictable, as well as controlling the video camera to follow the manipulator end-point.

7.3 Comparison of Manual Control Modes: Effects of Rate vs. Position Control and Large vs. Small Size

In general, rate control is slower than position control and separate control over each degree-of-freedom is slower than combined control (with a joystick). Position control with force-feedback (master-slave control) is faster than without force-feedback, and resolved-rate-control (where stick motion corresponds to cartesian-coordinates rather than joint-coordinates (achieved through computer coordinate-transformations) is faster than the less compatible arrangements.

Vertut (1973) has compiled a comparison of control modes for handling radio-active materials (Figure 7.1). Pesch (1976) has done the same for underwater manipulators (Figure 7.2). Both use the ratio of completion times for remote vs. direct human control as a summary measure. Mullen (1973), in a comparison highlighting resolved-rate-control, uses the ratio of completion times of the alternatives to master-slave control without force feedback, (Figure 7.3).

There are circumstances that may modify these consiusions. With a manipulator which cannot match human arm velocities, the advantages of position- over rate-control are reduced. Figure 7.4, which integrates experimental results of four different investigators who compared teleoperator to human operator task completion times, bears this out. Conditions variously used were resolved-motion rate control and master-slave position control, both with and without force feedback. Also, if extreme precision is required, there may be an advantage in being able to move only one joint at a time to avoid the inherent cross-coupling of different degrees-of-freedom which might occur with a joystick or replica (master) controller. For example, Black (1970) found with time-delayed manipulation (using

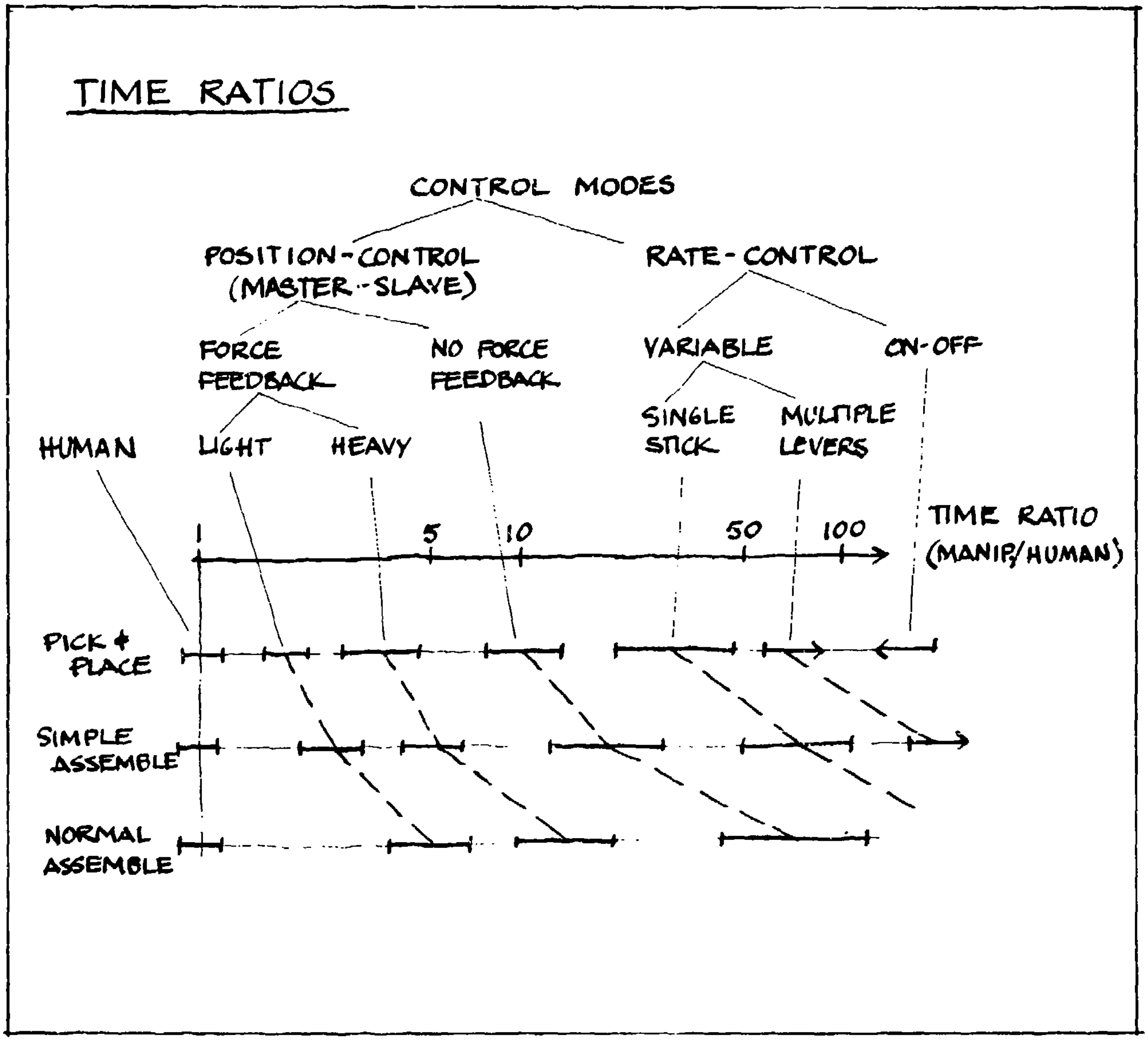


FIGURE 7.1 EFFECTS OF CONTROL MODE ON COMPLETION TIME can be compared on the basis of the ratio of time taken to do the task with manipulator divided by the time taken by a human (Vertut, 1976).

The best are master-slave manipulators with force-feedback which which are 2 to 10 times slower than the human hand depending on the complexity of the task.

Without force-feedback they are from 10 to 50 times slower than the human hand.

Single-stick rate-control (RMRC) is faster than multiple levers, and proportional rate control better than on-off-rate control. Some tasks are simply impossible without the compliance that force-feedback provides.

Currently, only one undersea manipulator (Oceaneering - G.E., Diver-equivalent-manipulator, DEM) is master-slave with force-feedback.

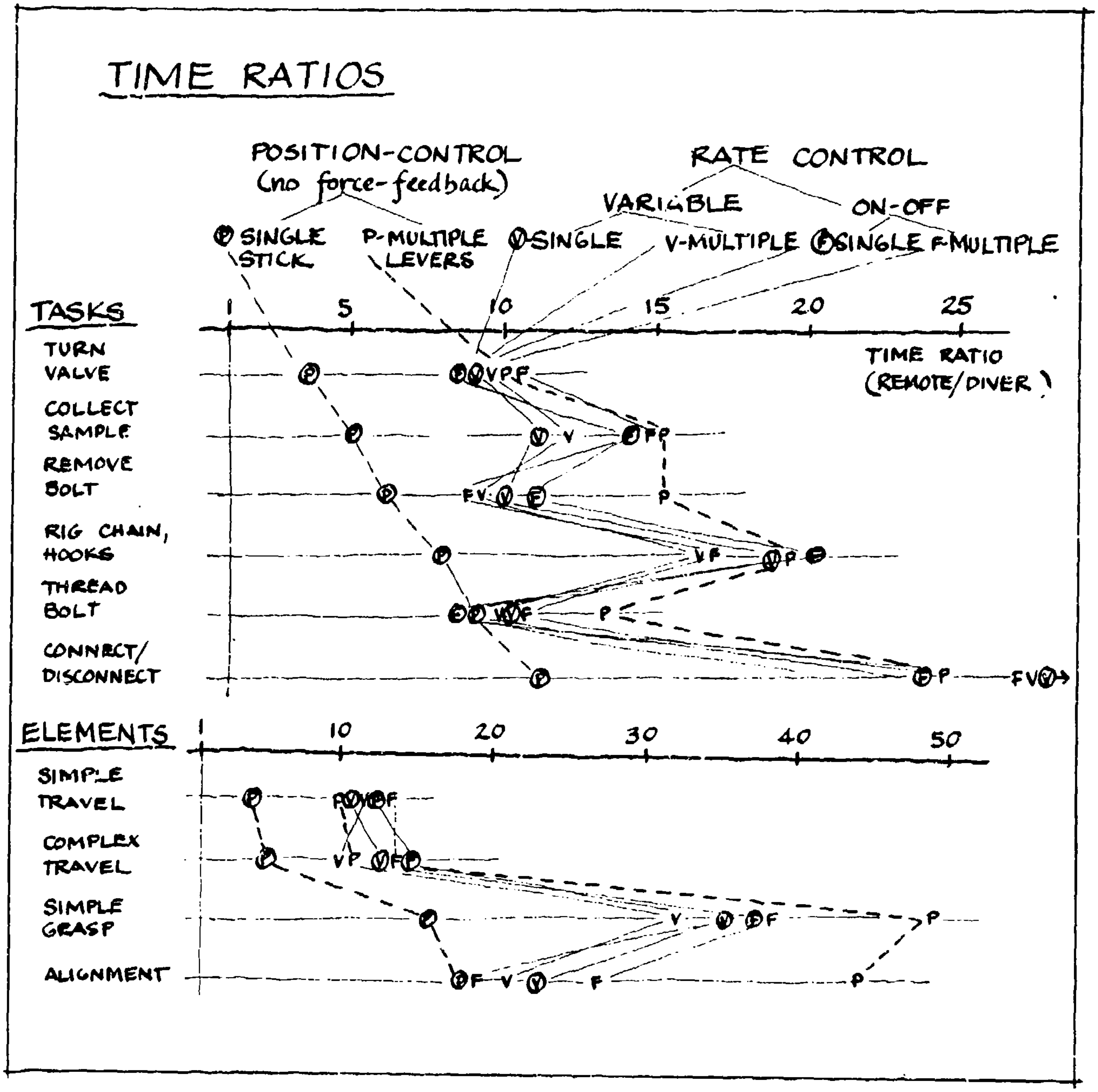


FIGURE 7.2 TIME RATIOS FOR UNDERSEA MANIPULATORS COMPARED TO DIVERS have been compiled by Pesch (1976).

This illustration summarizes some of these results, indicating: 1) widely differing effects of control mode; 2) widely differing effects of task performed. The diver in this case was operating under relatively ideal conditions and the teleoperator was relatively crude. Thus these may all be taken as "worse case" remote/diver ratios, where eventually many remote/diver ratios will be less than unity. Note that ratios for "elements" are larger than for "tasks". Presumably the very long "elements" in Pesch's study constitute small proportions of the total task time.

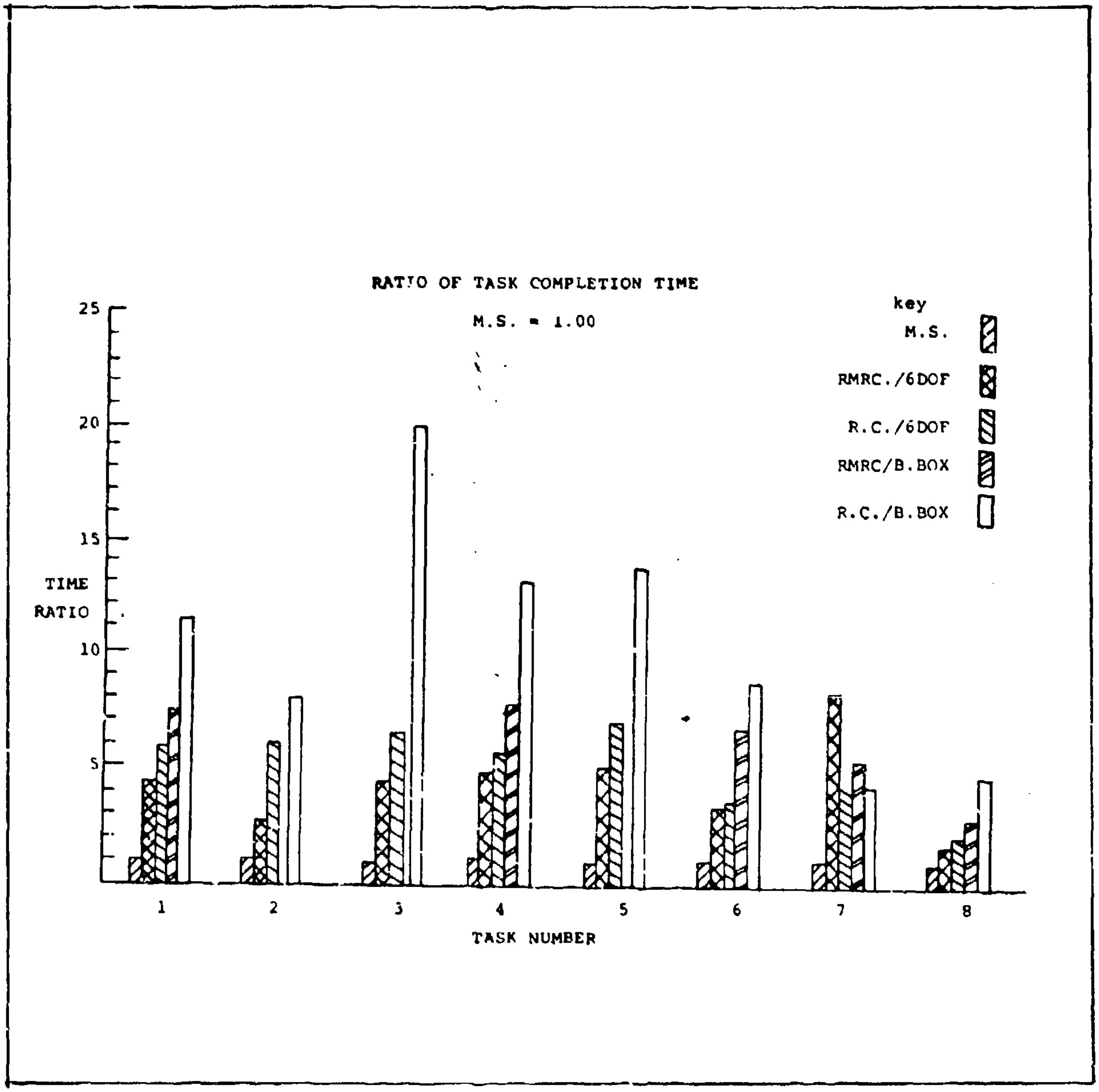


FIGURE 7.3 EVALUATION OF RESOLVED MOTION RATE CONTROL was carried out by Mullen (1973). Task completion time ratios are relative to the best manipulator control mode that he used (master-slave without force feedback). Depending on the task, he found RMRC to be from 2 to 8 times slower than master-slave. On the other hand RMRC was generally better than the other control modes he tried, the worst of which was rate-control with a button box which is the mode for most underwater manipulators.

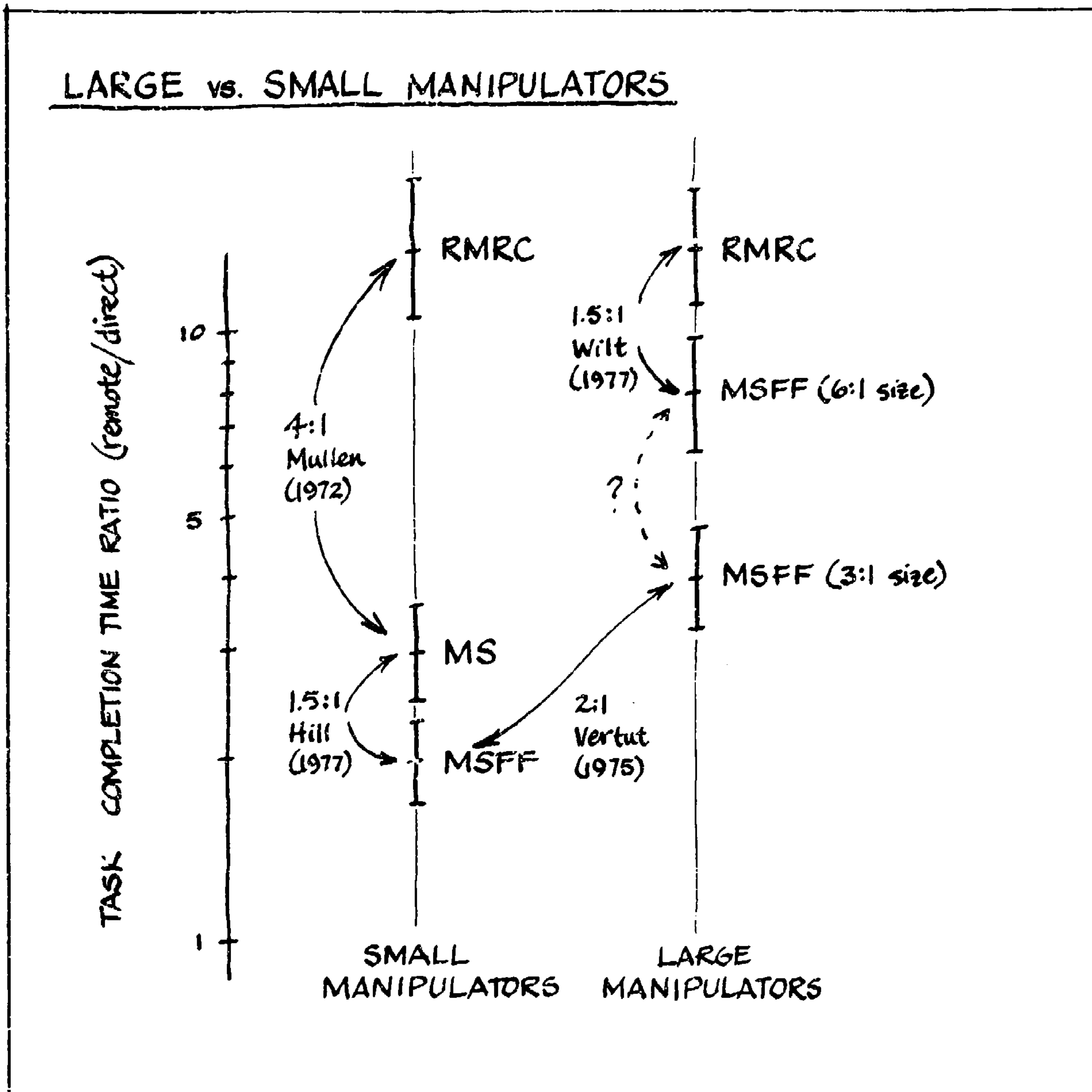


FIGURE 7.4 CONTROL OF LARGE VS. SMALL MANIPULATORS. By combining results from several investigators, it is possible to show that the time advantage of master-slave over rate-control is reduced for larger, slower manipulators.

Wilt (1977) compared "replica" master-slave control with force-feedback (MSFF) to resolved motion rate control (RMRC) for a large industrial manipulator (14 ft. reach, 24:1 force ratio, 6.2:1 size ratio). Mullen (1972) compared RMRC with master-slave control for a small manipulator but without force-feedback (MS). Hill (1977) compared MS to MSFF for small manipulators. Vertut (1975) compared large (3:1) to small (1:1) manipulators using MSFF.

master-slave with no force-feedback) that, while waiting for visual feedback, there was a drift or unintentional input by the operator who was trying to hold the master still. (The effects of time delay are discussed in more detail in section 7.5).

Finally, rate control might be of advantage over position control in a supervisory scheme if control is being traded from human operator to computer and back, thus minimizing the mismatch of operator command and computer command at the transition (i.e., the discontinuity would be in the rate, not in the position).

There are other factors which would enter into the choice of control mode (e.g., rate vs. position control) such as the space and weight required, and of course complexity and expense. We have no data to present here other than the task performance times.

For a task of transferring lead bricks in a nuclear hot cell, Vertut (1976) has shown that the time to move one block (cycle time) depends on the type of hand grip used and the ratio of force-feedback used (Figure 7.5).

7.4 Positioning Time vs. Accuracy: Fitts' Law.

A convenient summary model of human movement speed and movement accuracy is given by what has come to be known as Fitts' law. It quantifies two common experimental results: (1) movements of the same relative accuracy (distance A divided by tolerance W) appear to take the same time, and (2) there is a logarithmic relation between movement time and relative accuracy. (Fitts, 1954; Peterson, 1964). Using notions of uncertainty reduction from information theory, Fitts defined an index of difficulty (I_d) to include the ratio (A/W) and the logarithm so that completion time becomes a linear function of index-of-difficulty. The units of "difficulty" (with $\log_2$) become bits.

$$I_d = \log_2 \frac{2A}{W}, \qquad T_c = a + b\, I_d$$

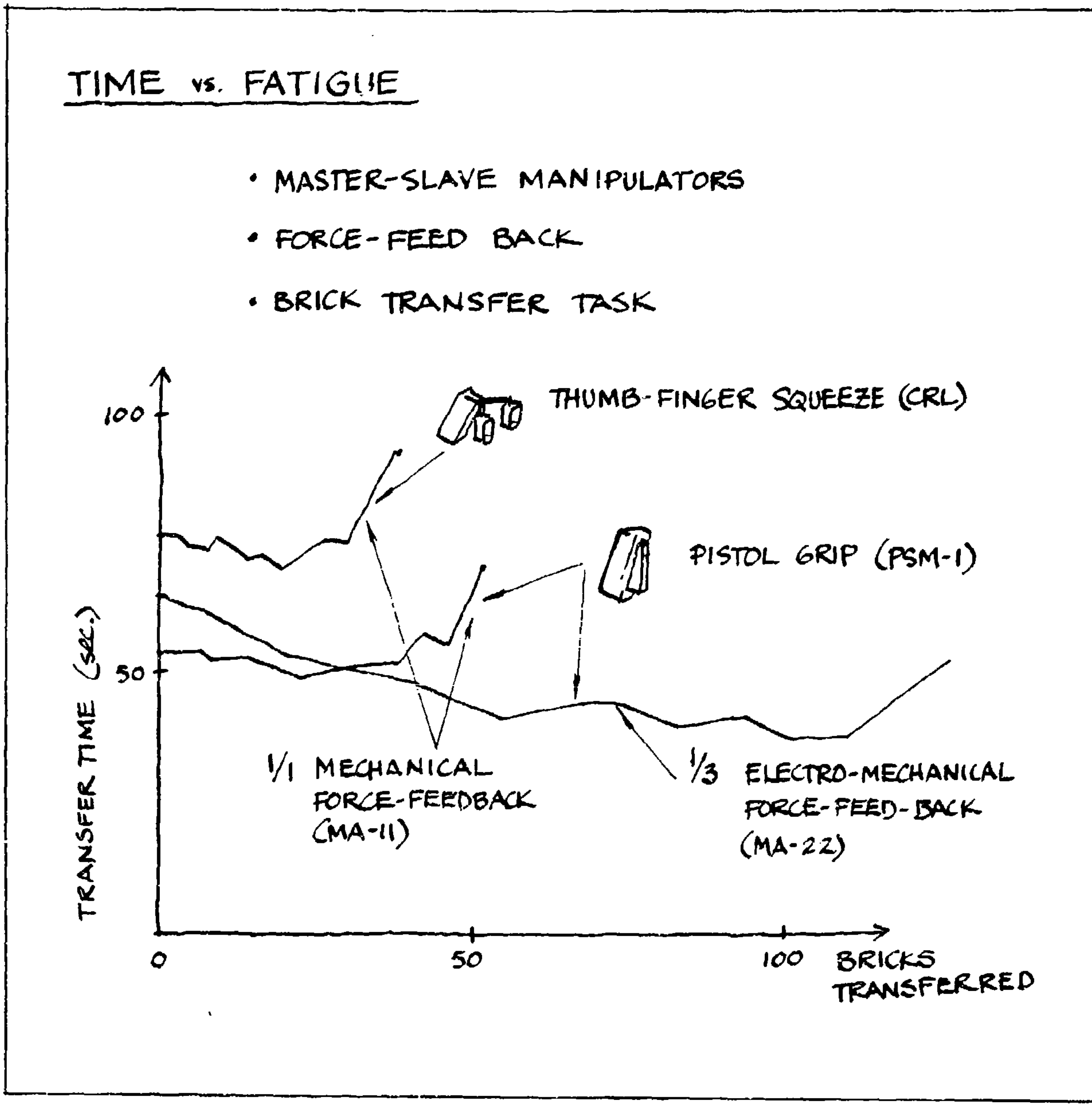


FIGURE 7.5 HANDGRIPS AND FATIGUE. There is not much data on long term performance and fatigue effects in manual control of manipulators. With master-slave force-feedback control, the operator must apply the same forces exerted at the remote end.

Vertut (1975) found that, for a test task of transfering lead bricks, proper hand grip design will reduce completion time for one transfer but that fatigue occurs almost as soon (approx. 50 transfers). Vertut found that by reducing the proportion of force fed back to the operator (3:1) he can work nearly three times as long without fatigue.

Several investigators have applied Fitts' law to describe performance of manipulator systems. Using two different manipulators, McGovern (1974) applied Fitts' law to two tasks, "pick-up-peg" and "put-peg-in-hole", varying distance (A) and tolerance (B-C), (see Figure 7.6). Roughly, completion times are equivalent for the two tasks; tasks of the same difficulty (I_d) take the same time, and average completion time (T_c) is proportional to difficulty. The same relationships were shown to hold for the two manipulators (Ames and SRI-Rancho) and for the unencumbered hand.

The proportionality of time and difficulty (with different slopes for different manipulators) supports the notion of using the ratio of completion times (manipulator vs. hand) as a key performance measure. At least, the ratio seems to be constant over a range of task-difficulties.

McGovern found the same ratio of completion times (manipulator vs. hand) for two different tasks and a different ratio for each manipulator (Figure 7.7). Pesch, Vertut and Mullen use similar ratios to compare control modes, but find different ratios for different tasks, requiring a variety of tasks for manipulator comparisons. This seems an appropriate outcome. The interesting thing from McGovern's work is finding that there are at least two tasks with the same ratio and that the ratio is constant over a range of task difficulties.

Open-loop positioning accuracy. Keele (1969) offers a derivation of Fitts' empirical law based on a simple assumed model of open-loop (eyes closed) positioning accuracy and a constant time (t) for each (discrete) feedback and movement. The assumption here is that, even when moving continuously, the human operator is making successive, discrete measurements. Movement time (T_m) is then simply proportional to the number (n) of "open-loop" moves (T_m = nt). If each movement has the same relative accuracy, $x_i / x_{i-1} = K$ where x_i is the mean absolute distance from the center of the target after the ith corrective movement, and if $x_0 = A$ is the starting distance, and $x_n = W/2$ is the final distance, where W is the width of the target, then

$$x_n = K x_{n-1} = K^2 x_{n-2} = \cdots = K^n A = \frac{W}{2}.$$

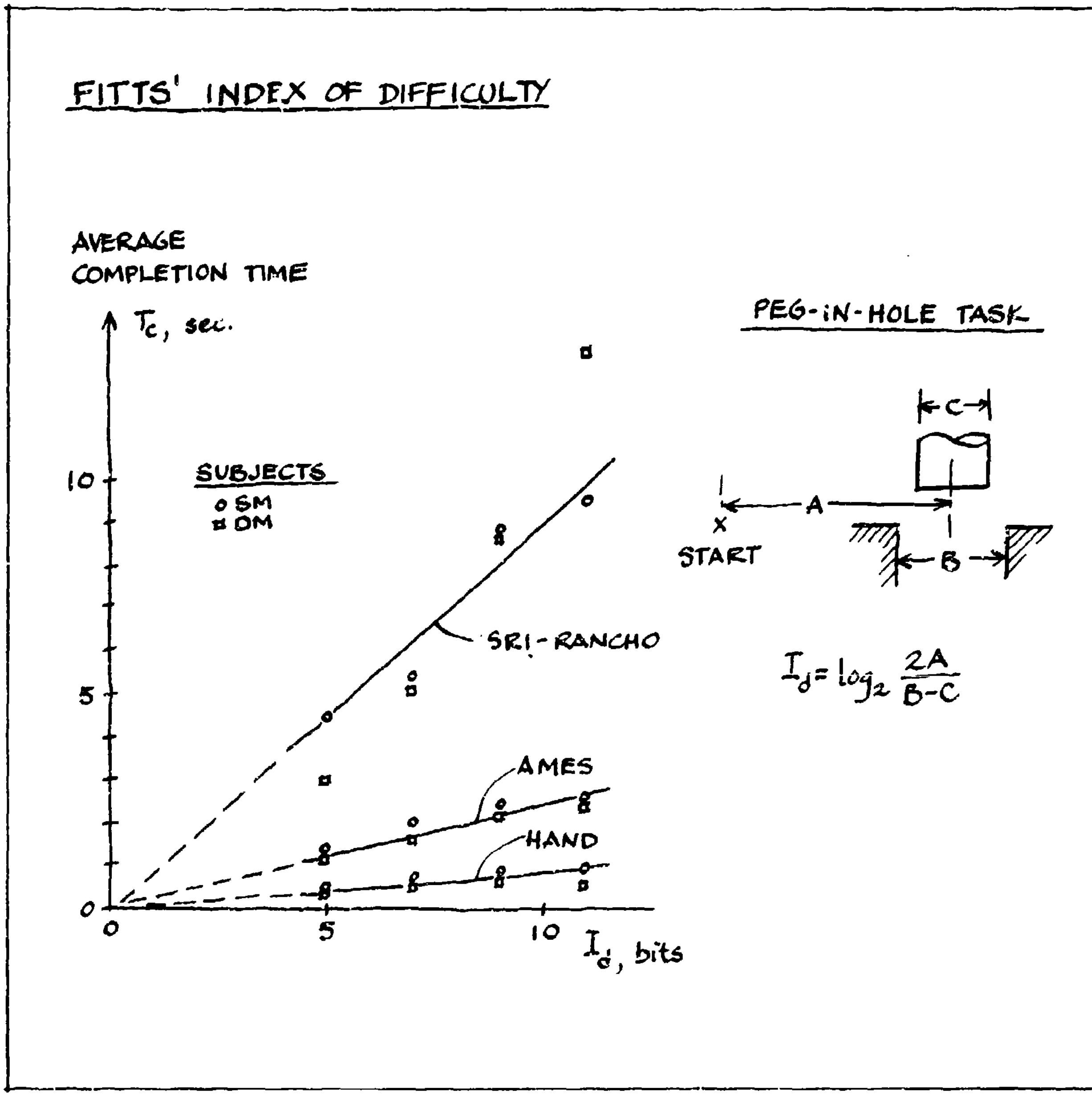


FIGURE 7.6 FITTS' INDEX OF DIFFICULTY is a useful measure of task difficulty.

McGovern (1974) used it to compare two different manipulators (both master-slave without force-feedback).

Roughly, over a range of distances (A) and tolerances (B-C), tasks of the same difficulty (A/B-C) take the same time, and time is proportional to the index of difficulty (I_d).

Proportionality of time and difficulty supports the notion of using the ratio of completion times (manipulator vs. hand) as a key performance measure. (AMES 3:1, RANCHO 10:1). Tasks other than peg-in-hole will produce different ratios. (McGovern, 1974).

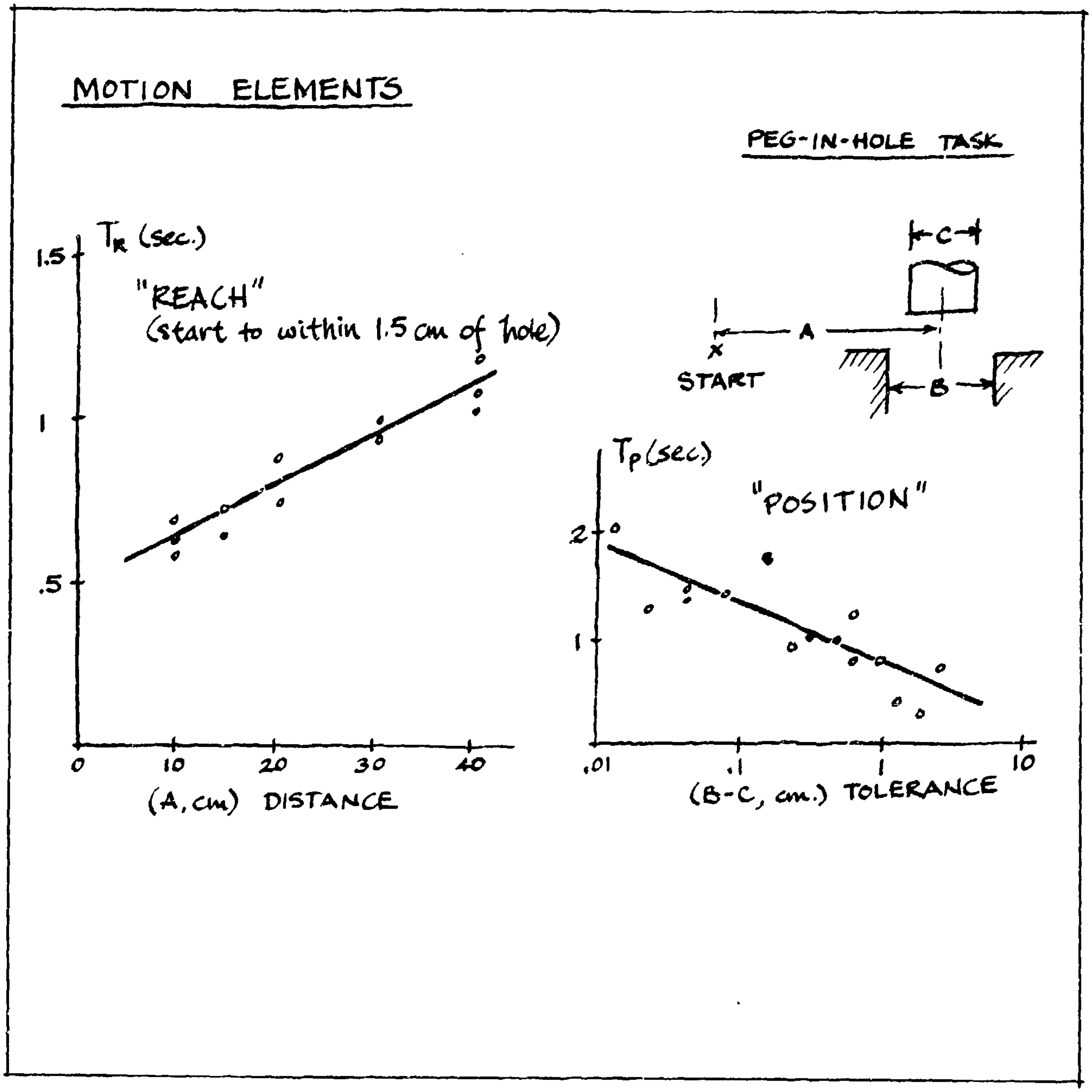


FIGURE 7.7 PREDETERMINED TIME SYSTEMS are used in industry to predict total task times from known times for motion elements. They require extensive calibration. No such data base exists for manipulators.

McGovern's (1974) detailed analysis of recordings of position versus time indicated that the peg-in-hole task can be divided into two phases as in MTM: "reach" and "position". The "reach" phase is from start to within 1.5 cm of the hole. "Reach" time is linearly related to distance and independent of final tolerance. "Position" time is independent of distance and best modelled as a logarithmic function of tolerance.

This data was later used by McGovern to predict the value of an automatic subroutine, GROPE, which replaces the "position" phase.

Therefore,

$$n = \frac{-\log \frac{2A}{W}}{\log K}$$

and

$$T_m = \left(\frac{-t}{\log K}\right) \log \frac{2A}{W} = b\,I_d \quad \begin{cases} b = \left(\frac{-t}{\log K}\right) \\ I_d = \log_2 \frac{2A}{W} \end{cases}$$

which has the same form as Fitts' law except for Fitts' additive constant, a. Such a constant would be needed to fit the data, for example, if the first or last move were slower or faster than the rest,(or the initial time to decide about target distance were included), Keele uses t = 260 msec. and K = .07 from independent experiments and predicts a value of b = 70 msec. which is very close to the value found by Fitts.

7.5 Remote Manipulation with Transmission Delay

Studies of delayed auditory feedback showed that speaking under such circumstances is practially impossible. There were fears expressed that delayed visual feedback (as in remote manipulation at lunar distance) would make manipulation impossible. Ferrell (1965) showed that it is possible, just time-consuming. The human operator adopts a "move-and-wait" strategy, making a succession of openloop moves and waits for feedback. Because of this move-and-wait strategy, Ferrell showed that it is fairly straightforward to predict exactly what the effects of increased time-delay are going to be. The extra time is simply proportional to the number of waits (or open-loop moves) necessary to accomplish the task. Ferrell's results are shown in Figures 7.8 and 7.9.

Ferrell looked in detail at the issue of open-loop movement accuracy, using a simple two-degree-of-freedom-plus-grasp master-slave manipulator. He found that the standard deviation of movement error was not a linear function of distance (as Keele assumed), and that a better fit was variance

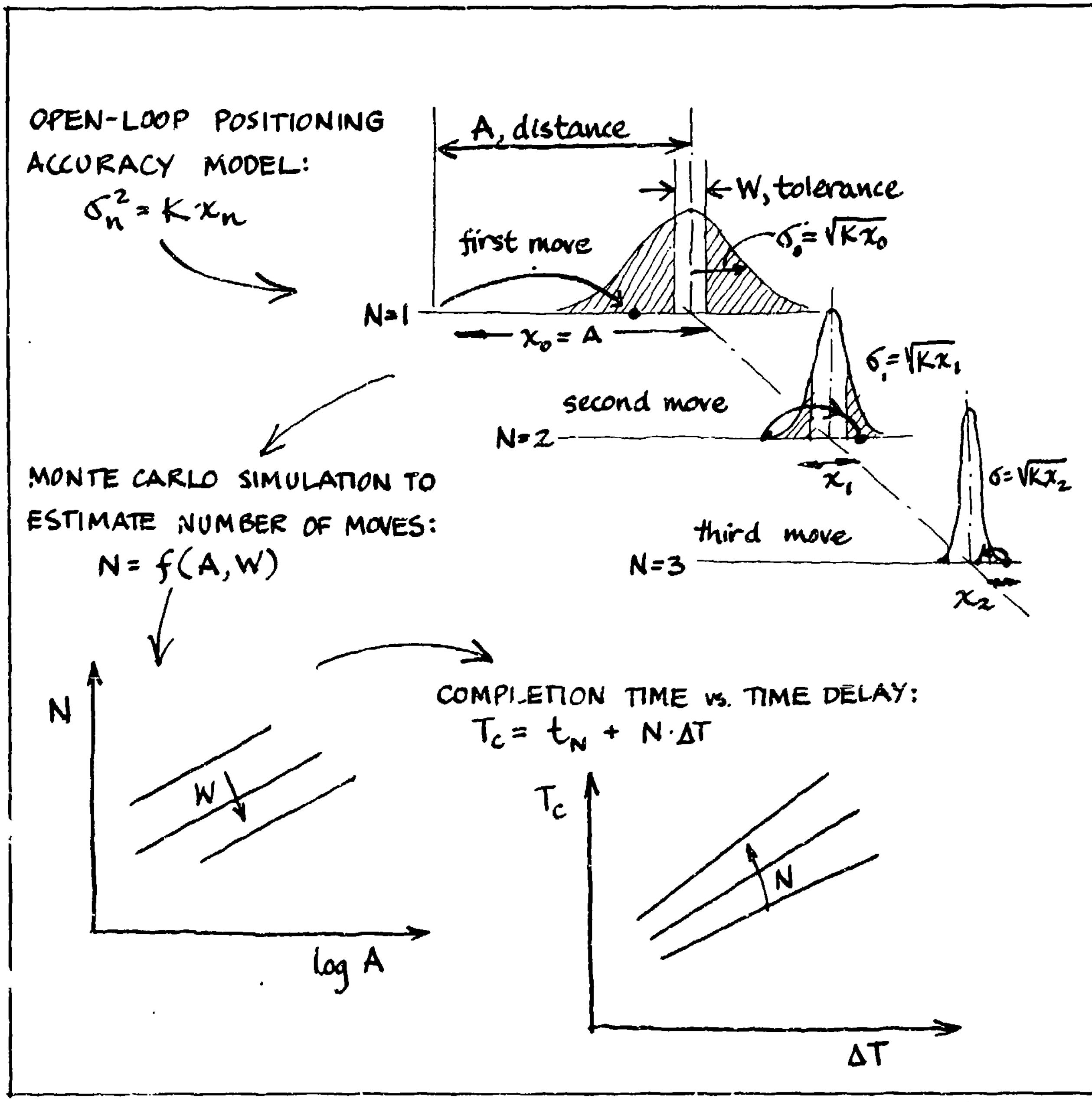
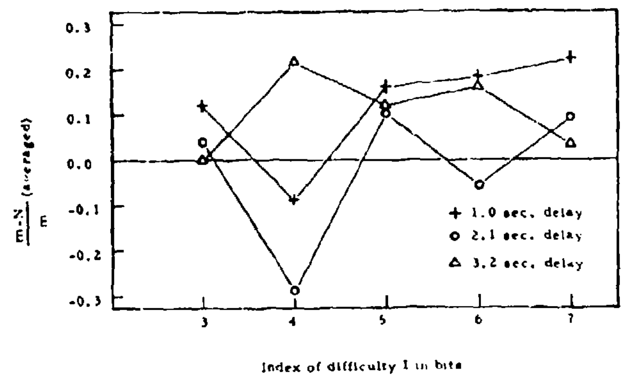


FIGURE 7.8 FERRELL'S METHOD OF MOVEMENT TIME ESTIMATION for remote manipulation with time-delay is based on the fact that the operator makes a series of blind moves and then he waits a delay-time (ΔT) for feedback. The additional time with longer delay-time is simply proportional to the number of moves.

The number of moves can be estimated as a function of movement distance and tolerance from a simple model of open-loop movement accuracy by using Monte Carlo simulation.



Relative error in estimating the number of pauses for feedback: simple task.

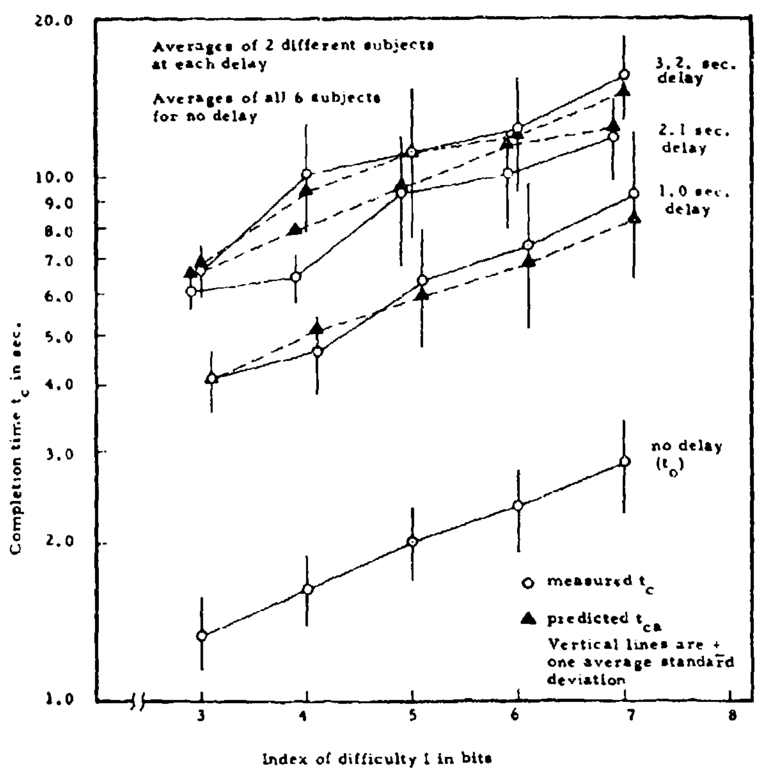


FIGURE 7.9 FERRELL'S RESULTS in comparing predicted to actual number of moves and predicted to actual completion time. (Ferrell, 1965).

proporational to distance ($\sigma_x^2 = KA$). His experiments used different target distances for successive moves; repetitive moves to the same target distance would have been more accurate. With this assumption ($\sigma_x^2 = KA$) he calculated (using Monte Carlo simulation) the number of open-loop moves necessary to reach a given tolerance. In contrast, Keele's derivation neglects probabilities and assumes that each open-loop move is always the same proportion of the distance to the target. Ferrell's theory is based on a Gaussian distribution of end-points of open-loop moves with variance (not standard deviation) proportional to distance. The number of moves predicted is roughly proportional to Fitts' index of difficulty but the curve shifts up (more moves) for greater distance. This simple model of open-loop uncertainty accounted quite nicely for most of Ferrell's results. Black (1970) studied time-delayed manipulation (3 sec.) with a 6 degree-of-freedom-plus-grasp manipulator (Argonne E-2 master-slave with force-feedback removed) and confirmed Ferrell's findings of the move-and-wait strategy. Black's analysis of video tapes revealed that different elements of the task required different numbers of moves (Figure 7.10). Time per move averaged five seconds, no matter what portion of the task was considered. This is explained by the majority of that time being spent waiting (3 seconds per move).

Those portions or elements of the task which required the greater number of moves required a larger percentage of total task completion-time with the delay as compared to without the delay. This result is illustrated in Figure 7.11.

More recently Thompson (1977) measured task completion time with varying degrees of task constraint (using Hill's tasks, Figure 3.12) and with two different manipulators plus direct human manipulation. The results are given in Figure 7.12. Thompson also studied the effects of loop time delay on performance on the same set of tasks, using the NASA Ames master-slave manipulator (see results in Figure 7.13).

Starr (1976, 1978) compared position vs. rate control with time delay.

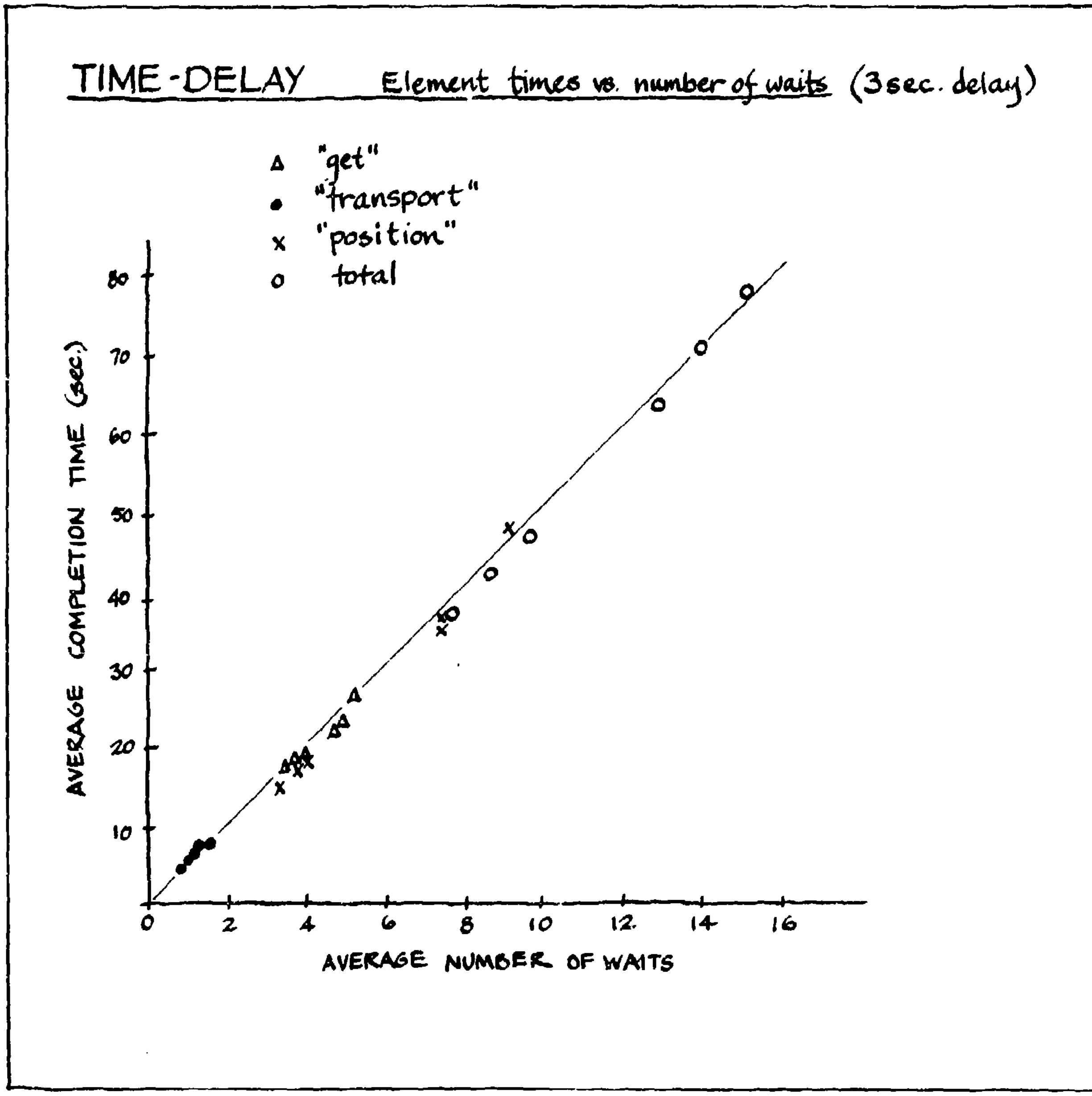


FIGURE 7.10 TIME-DELAY. Master-slave manipulation with a 3-second time-delay is characterized best by the move-and-wait strategy used. Completion time is dominated by the amount of time spent waiting.

Black (1970) counted the number of waits for feedback from video tapes. No matter which task element was being performed (get, transport, position) completion time is proportional to number of waits. This emphasizes the importance of open-loop movement accuracy from which the number of waits can be predicted (see Figure 7.8).

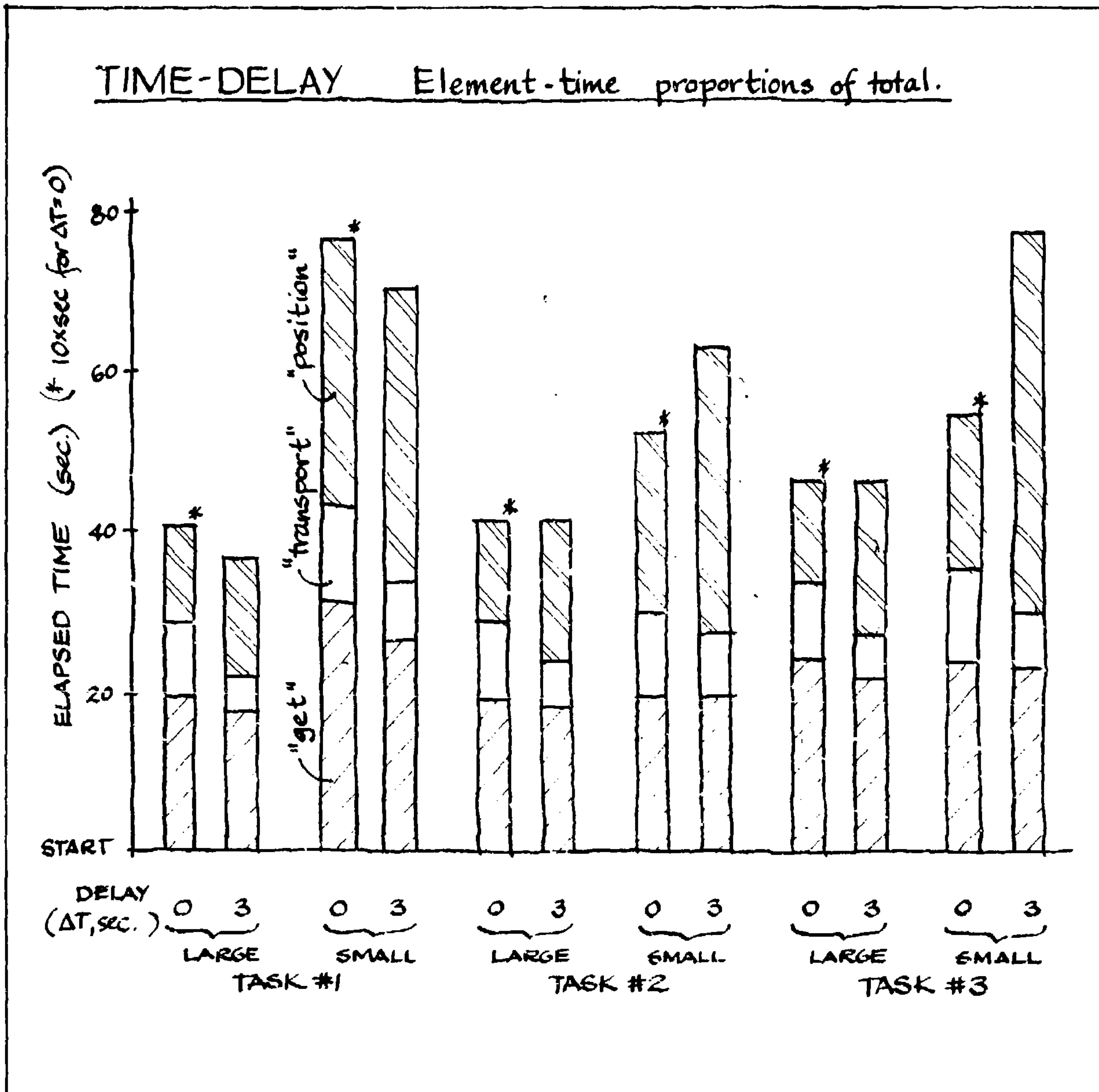


FIGURE 7.11 ELEMENT TIME PROPORTIONS change with time-delay depending on the number of movements required. "Transport" (1 - 2 moves) becomes a smaller fraction, "Get" (4 - 6 moves) stays about the same, and "Position" (4 - 10 moves) becomes a larger proportion of the total task time. (Black, 1970).

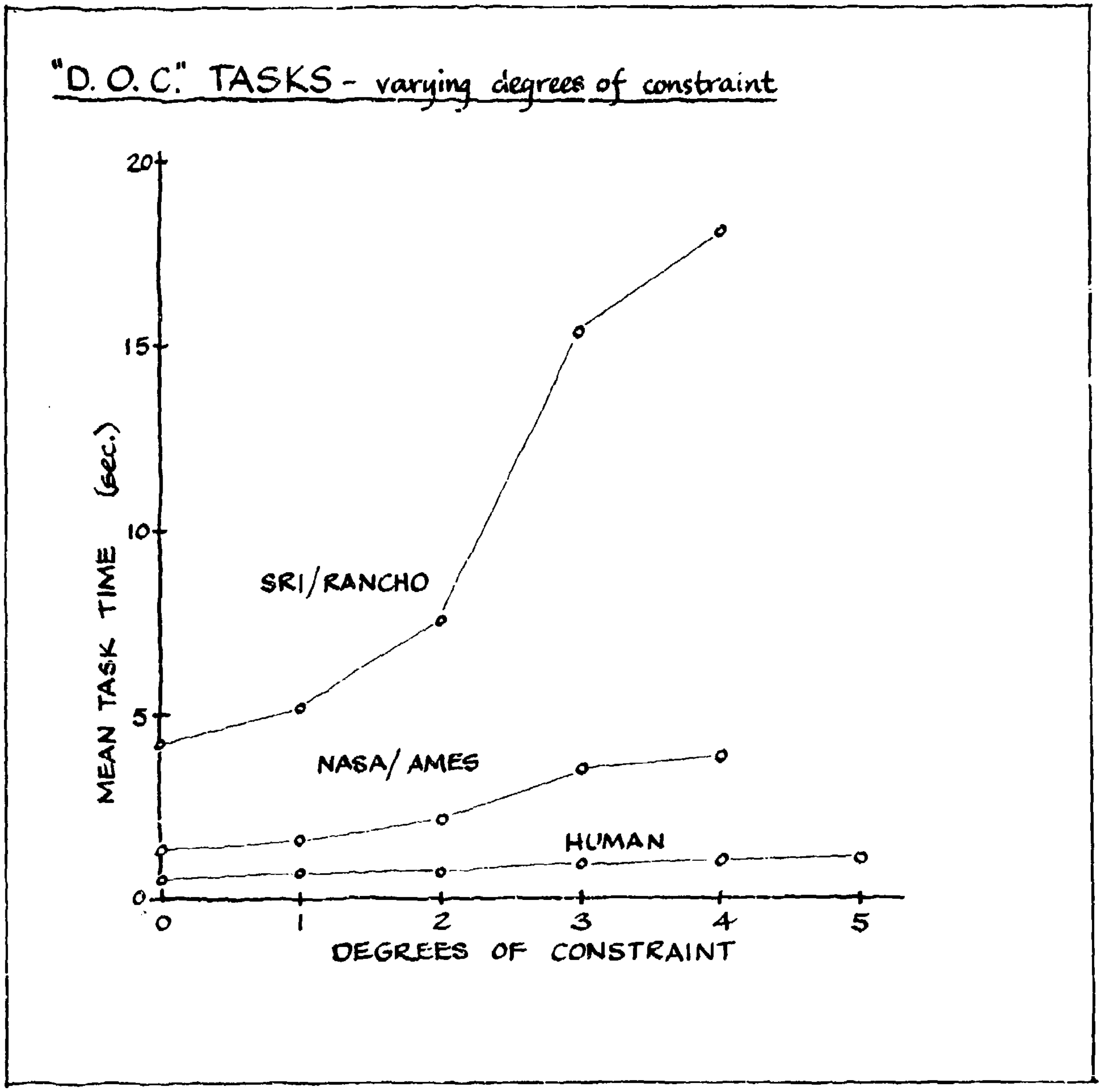


FIGURE 7.12 VARIABLE DEGREE-OF-CONSTRAINT TASKS were used by Hill (1976) to compare two manipulator systems with the human hand. The tasks are shown in Figure 3.12. Thompson (1977) used the same tasks for a study of time-delay (Figure 7.11).

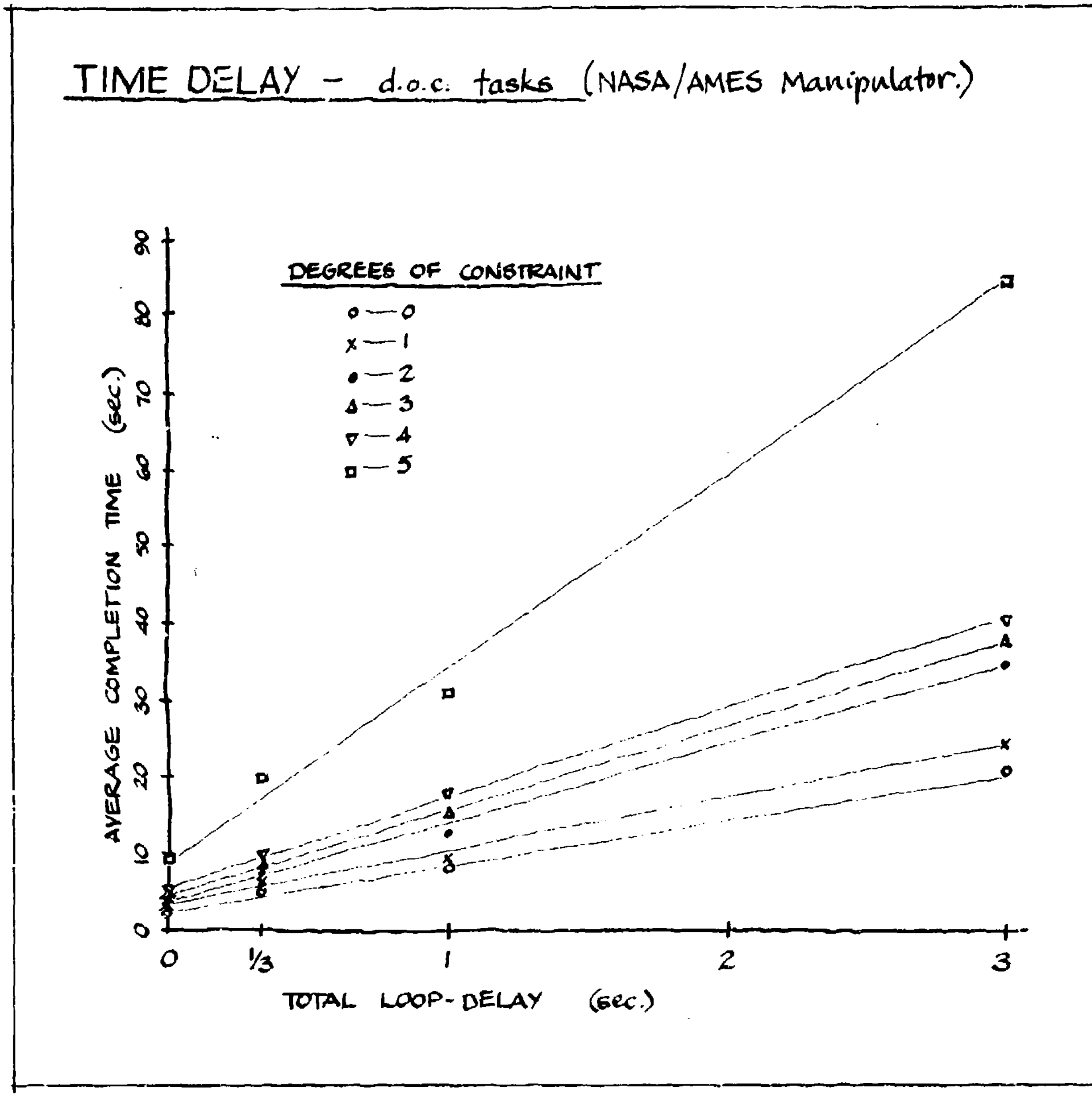


FIGURE 7.13 EFFECTS OF TIME-DELAY ON COMPLETION TIME are compared for six different tasks. This is a replot of data from Thompson (1977) to show that there is a linear increase in completion time as a function of time-delay. The slope of the line, as shown by Ferrell, is simply the number of open-loop moves necessary to complete the task (ranging from 6 for the 0 d.o.c. task to 27 for the 5 d.o.c. task).

He found that over a range of time delays up to 3 seconds the advantage of position control over rate control is reduced as time delays get larger.

Delayed force-feedback. The advantage of force-feedback in master-slave manipulation may turn to difficulty with a time-delay in the control loop. Ferrell (1966) has shown that if forces are fed back to the hand which also provides the positioning command to the manipulator, they will tend to move the operator's hand. If the delay and the rate at which feedback force changes with the position of the remote hand are great enough, a manipulator can become unstable. Unstable movements can easily be avoided with purely visual feedback since the operator can attend to the information selectively; and error indication need not result immediately in a response by the operator. Ferrell suggests displaying the delayed force information to the other hand or having some mechanism at the remote end for limiting applied forces.

A careful distinction should be made between the transportation time for a signal and the transmission time for a complete message. The signal transportation time via electro-magnetic radiation is the distance divided by the speed of light. Round trip to the moon for transport time-delay is about three seconds. This was the basis for the choice of time-delay in many of the experiments on time-delayed manipulation which NASA has sponsored.

The transmission time for a message depends on the capacity of the channel (bits per second) and the information in the message (bits). Encoding (for error correction redundancy) and validation may further increase the time for complete transmission of a message. For example, a high resolution T.V. image requires 3 million bits; at 10,000 bits/second (a good underwater voice channel) this would require 300 seconds (i.e., 5 minutes) per frame. Remote manipulation undersea through such a data link will be limited by the slow frame rate, not by the transport time-delay.

The laboratory results for time-delayed manipulation may or may not be

relevant to the situation of slow frame rate, which may characterize future undersea teleoperator systems. The move-and-wait features of self-paced performance will probably be the same but the difference between having a moving picture (time-delayed) and a still picture (slow-frame-rate) may produce very different performance. Ferrell's use of an underlying relationship between open-loop movement distance and accuracy may be the key to modelling and predicting performance. For example, the trade-off between frame-rate (frames per second) and resolution (bits/frame) might be predicted through such a simple model which includes less accuracy at lower resolution.

7.6 Remote Vehicle Control with Transmission Delay and Slow-Frame-Rate

Section 5 describes a predictor display system for coping not only with transmission delay but also with slow frame rate. Verplank (1978) explored the effects of such a predictor display for vehicle control. An interactive simulation was written on an Interdata 70 computer and Imlac graphic display. A random terrain was generated and displayed in perspective, updated every 8 seconds, to simulate the pictorial information. A moving predictor symbol was generated representing the vehicle as a square in perspective. Two straight ridges were added to the random terrain to serve as a test course. (Figure 7.14).

The simulated vehicle was controlled by the operator with a spring-centered 2-degrees-of-freedom joystick. The dynamic response of the vehicle was a simple integration with forward speed proportional to forward-back position of the stick and turn-rate proportional to left-right position of the stick. The vehicle was always the same height above the terrain (simulating automatic altitude hold). No disturbances such as currents were simulated. Also, it was found important to have a good detent and dead-zone on the stick to avoid inadvertent commands.

A stationary "table" was drawn to indicate where the next picture was to come from while the "real-time" predictor continued to move in response to the operator's commands (Figure 7.14). Dotted lines were added to this

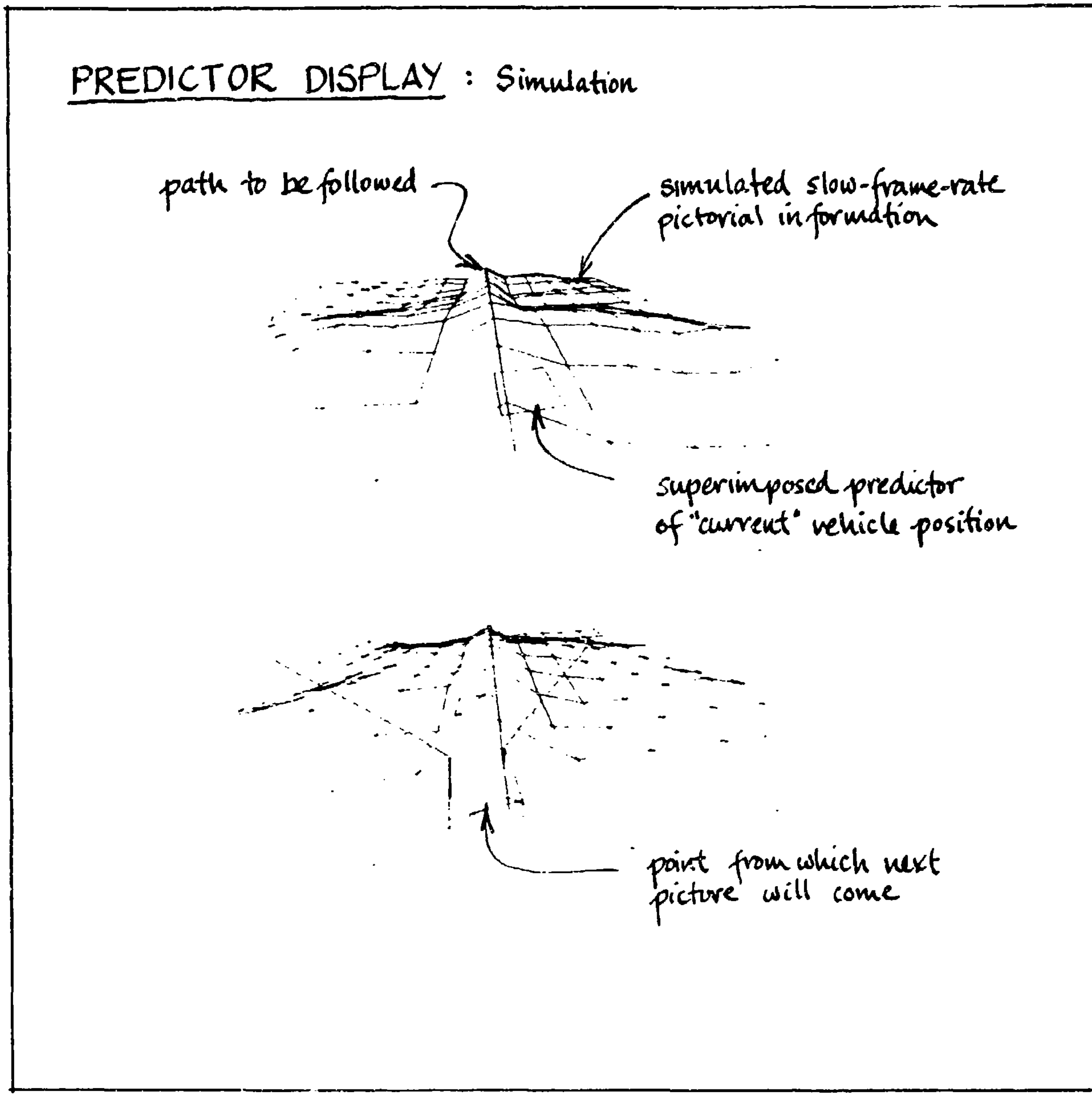


FIGURE 7.14 SIMULATION EXPERIMENTS WITH PREDICTOR DISPLAYS were performed by Verplank (1978). Slow-frame-rate pictures (8 seconds per frame) were simulated by computer-displayed terrain. The path to be followed was a ridge in the terrain.

A moving predictor symbol (perspective square) was superposed on the static picture of terrain. The point from which the next picture was taken was indicated with a "table" (square with four legs) and the field of view was shown with dotted lines.

table to indicate the field of view. This reduced the considerable confusion about how the picture was expected to change and served as a guide for keeping the vehicle within its own field of view, which is the best strategy for using this kind of predictor on the pictorial display.

A typical trajectory, without the predictor, is shown in Figure 7.15a. The dotted lines represent $\pm$ one terrain-unit from the ridge. The circles represent the vehicle's position every 2 seconds. V's represent the field of view of each picture sent. Quite often there is no movement between successive dots (2 secs.) or successive pictures (8 seconds)

Only with extremely slow speed was it possible to keep track of the ridge. Approximately five minutes and 40 pictures were required to traverse just one of the ridges (half the course). This is shown in Figure 7.15b.

With the predictor symbol, practially continuous motion was possible. A typical trajectory is shown in Figure 7.16a. The course was completed in 3 minutes and 23 pictures.

A typical trajectory in request mode (where pictures are only sent by operator request, as explained in Section 5.3) is shown in Figure 7.16b. Compared to periodic mode, the time is about the same but the number of pictures used is one-half to one-third; velocities are higher but there is a wait for 10 seconds as each picture is taken and sent.

For the conditions studied (T = 1 sec., S = 8 sec.) manual control is not feasible without display aids such as the predictor symbol. The request mode is preferred as it seems to avoid confusion and reduce the number of pictures necessary.

7.7 Viewing Conditions for Remote Manipulation

For remote manipulation the primary mode of feedback to the operator is visual. The only means presently used is television. (For a manned sub-

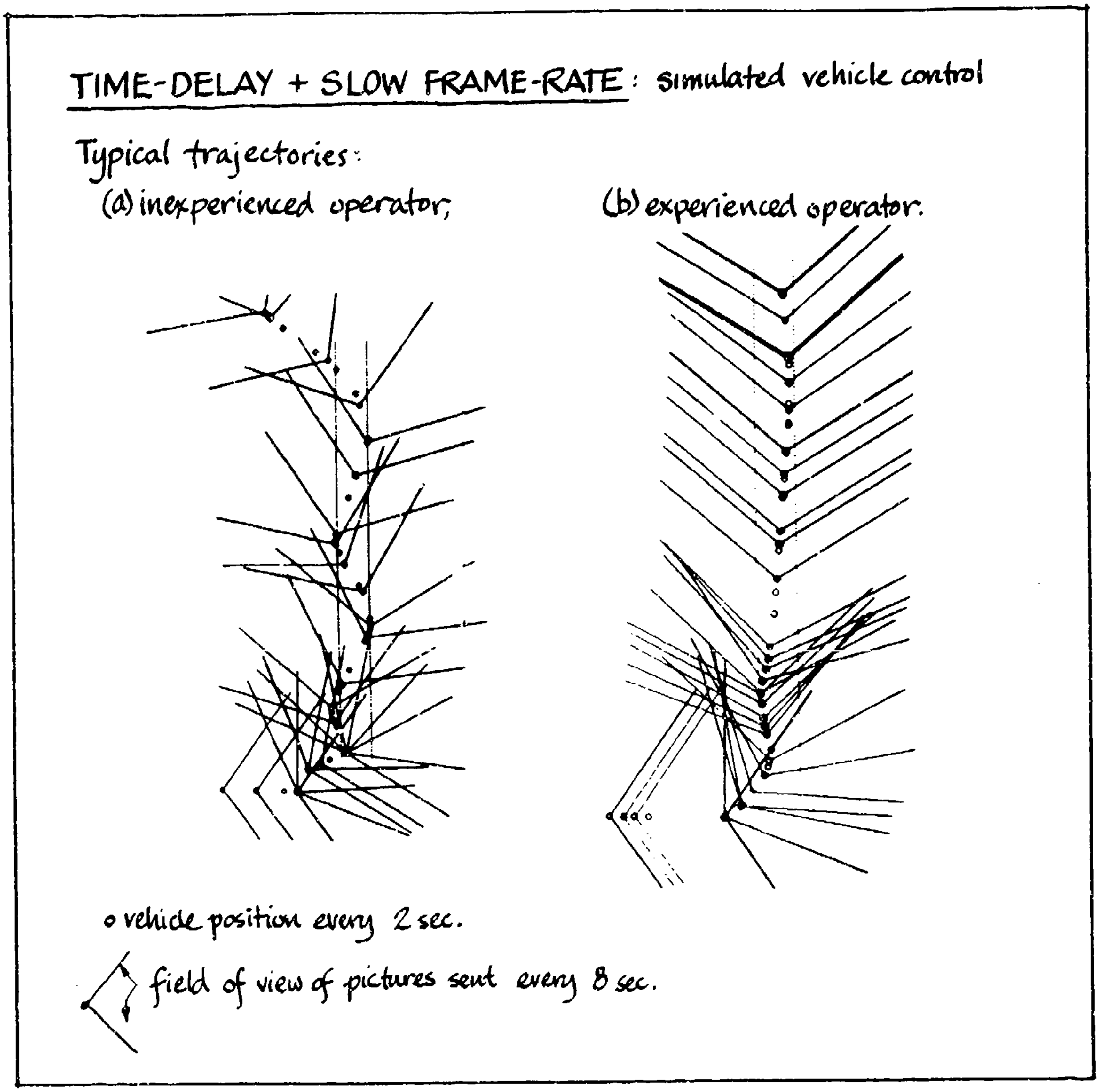


FIGURE 7.15 REMOTE VEHICLE CONTROL WITHOUT A PREDICTOR is difficult when the only information is a time-delayed slow-frame-rate picture. The tendency at first is wild oscillations (a); only with practice and very slow speeds is control possible (b).

These results are from a simulation of one picture every 8 seconds delayed by 1 second. (Verplank, 1978).

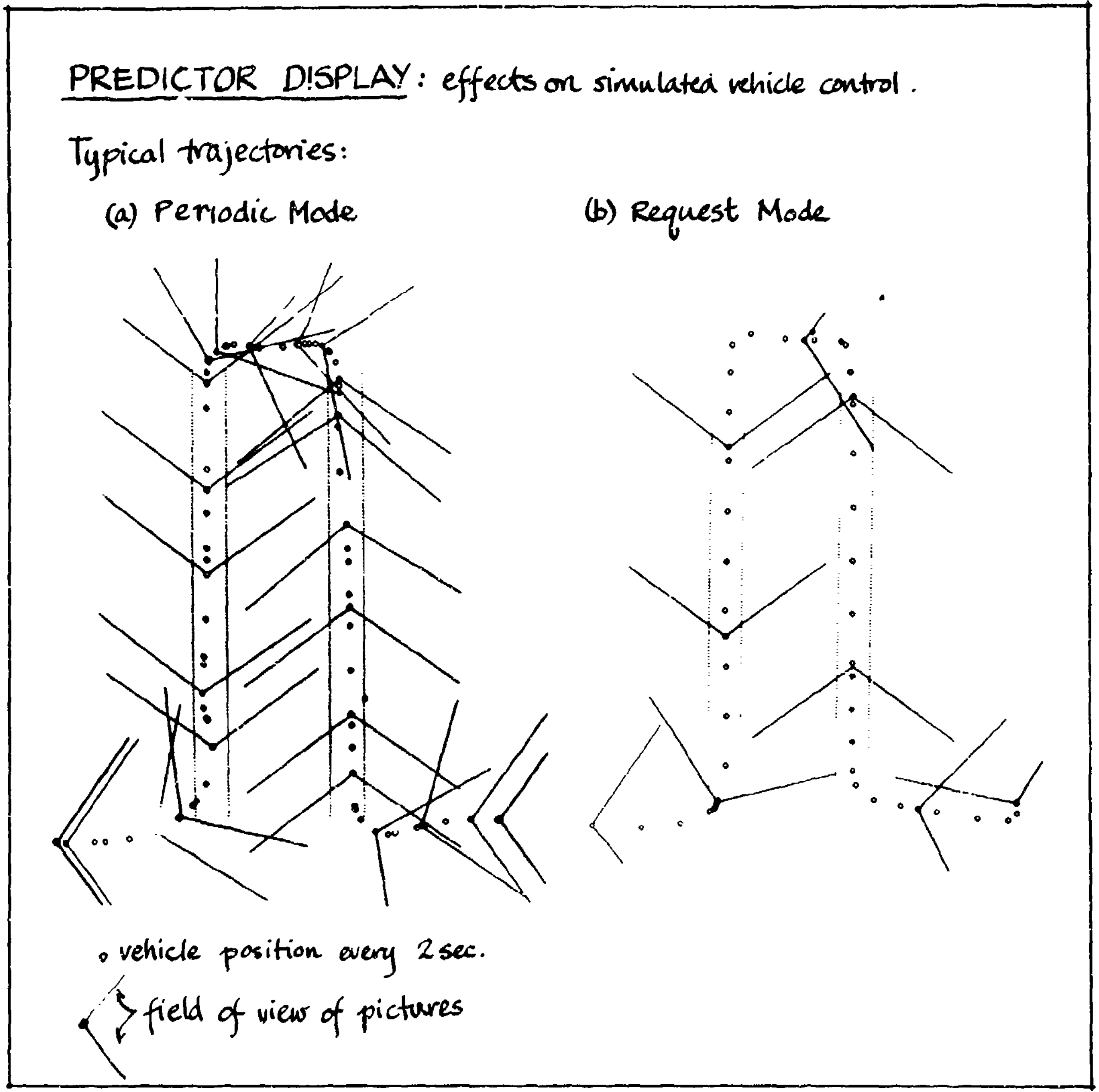


FIGURE 7.16 SIMULATION RESULTS WITH PREDICTOR DISPLAY show good remote vehicle control in spite of slow frame rate (8 seconds/frame) and time-delay (1 sec). In periodic mode, (a), one picture is sent every 8 seconds; in request mode, (b) pictures are sent only upon the operator's request. Travel times are equivalent for the two modes; request mode uses fewer pictures but requires a 10 second pause in vehicle motion as each picture is sent. (Verplank, 1978).

mersible, direct viewing through a port is also used.)

One of the natural things to try for remote viewing is stereo. On the whole, results have been disappointing. There are many practical problems. Stereo television is more complex and expensive; usually it is less reliable. The resolution can be poorer, and the viewing apparatus an encumberance. There are many subtle errors possible with mismatched lenses, and non-linearity in image transfer. (The distortion might not be distinguishable from depth dues). Control over focus and convergence is complex and inconvenient.

There is significant learning for manipulation through either stereo or mono-television. In fact, the differences between mono and stereo (task completion time and errors) appear to be reduced with practice (Pepper, 1977). See Figure 7.17a.

The possible advantage of stereo over mono viewing may be greater for turbid water. The particles intervening between object and lens will be different in the two views. The human observer's natural correlation of the two views serves to "filter" the "noise" of uncorrelated particles. The predicted effects of turbidity are shown in Figure 7.17b.

There are, of course, other methods of picking up depth cues: a second view from another camera (or from the same camera after moving it), the differing amounts of intervening turbidity, varying amounts of illumination, shadows, markings on objects. Color may or may not be an advantage; the added cues are at the expense of the sensitivity and resolution possible with high quality black and white cameras and monitors.

NASA sponsored a comprehensive, multivariate laboratory study of viewing conditions for remote manipulation in space (Freedman, 1977). The results are summarized in Figure 7.18. The only variables which affected task completion time significantly are the task, arm speed, and the TV system (mono- B+W more time than stereo). On the other hand, when position error is of concern, the two-view TV system is better than all the others

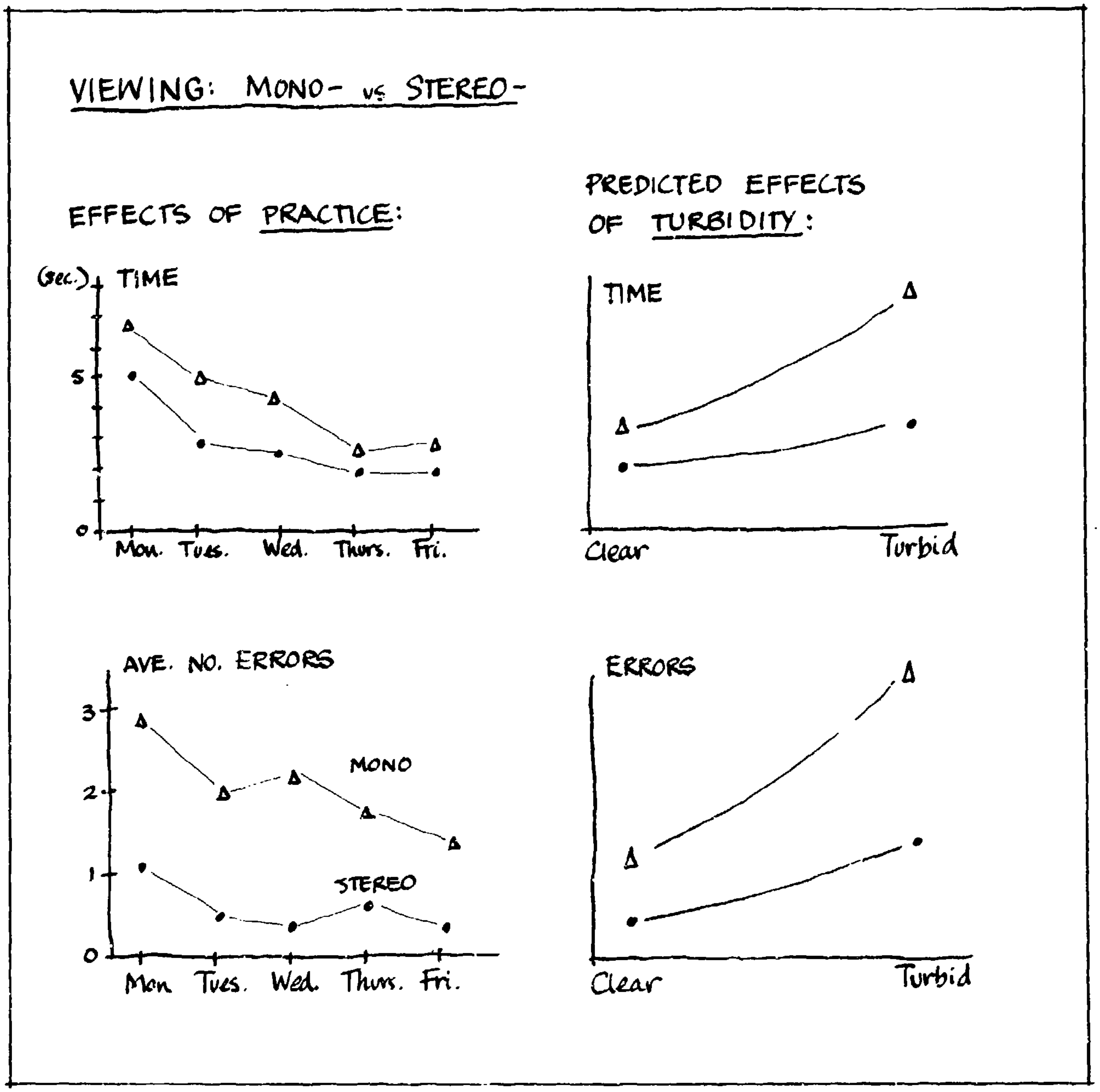
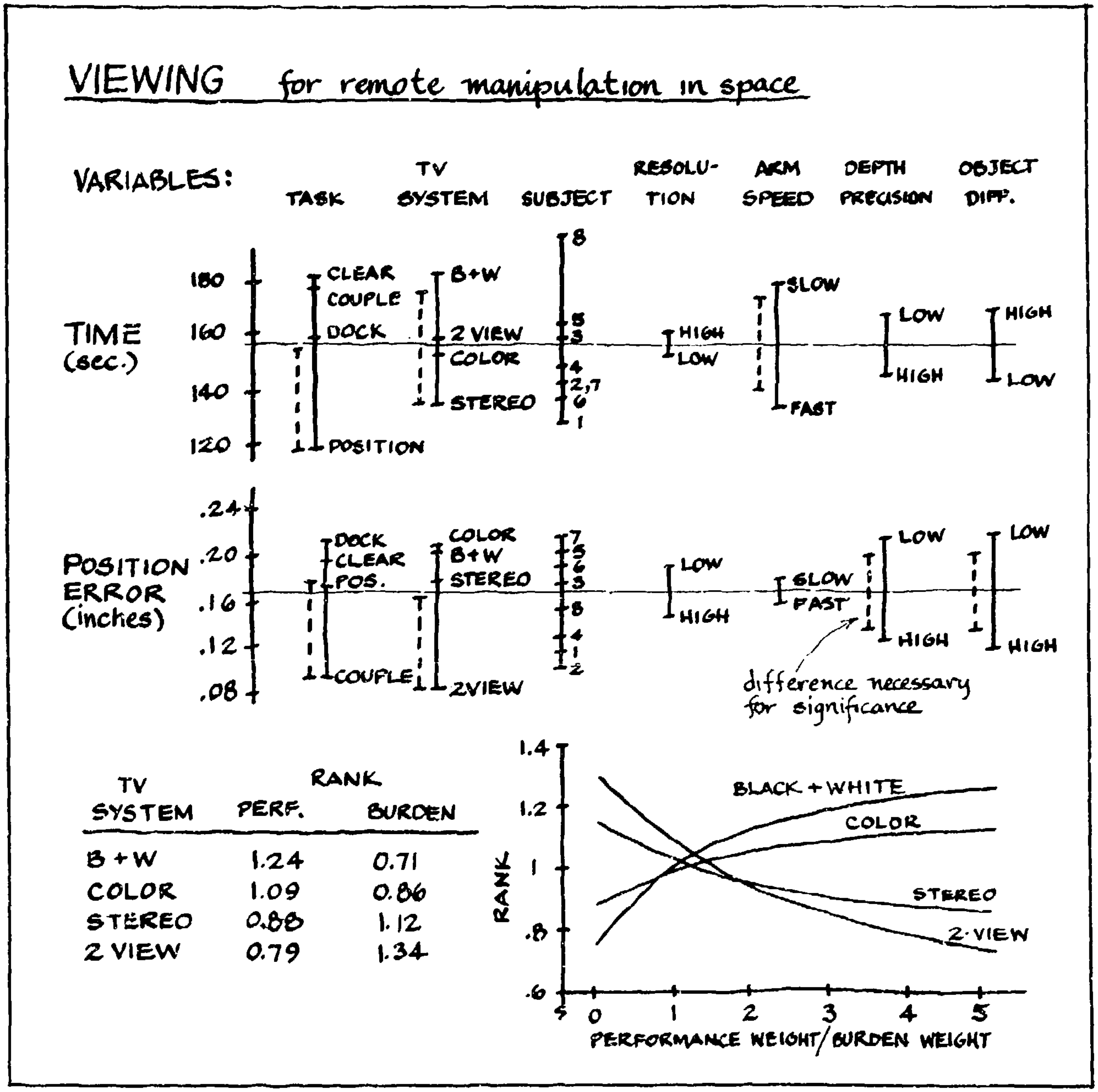


FIGURE 7.17 STEREO- VS. MONO-VIEWING was studied by Pepper, et al. (1977) for a simple manipulator positioning task in a fairly complex scene which simulated underwater conditions. Stereo was always better than mono especially in terms of contact errors, but the differences were reduced with practice.

The advantage of stereo might be greater in turbid water. This is illustrated with the hypothetical curves on the right.



TV SYSTEM	RANK PERF.	RANK BURDEN
B + W	1.24	0.71
COLOR	1.09	0.86
STEREO	0.88	1.12
2 VIEW	0.79	1.34

FIGURE 7.18 VIEWING FOR REMOTE MANIPULATION IN SPACE was studied in a multi-variable laboratory simulation. (Freedman, et al. 1977). Time and error averages are shown for each independent variable in comparison to the grand mean (horizontal line). The difference necessary for significance is shown with the dotted vertical lines (where there is none there were no significant differences).

TV system rankings were made for over-all performance and burden (cost, weight, etc.). B&W mono is best (lowest combined rank) when burden is more critical; 2-views are better when performance is more critical than burden.

Figure 7.18). (Means not separated by more than the length of the dotted lines are not significantly different; for variables with no dotted line shown, there are no significant differences.)

Freedman's summary recommendations considered two measures of each TV system: an over-all performance rank (smaller rank is better) and a burden rank (smaller burden is also better) based on cost, complexity, reliability, weight, etc. For example, the two-view system ranked best for performance but worst for burden, The black and white mono system was ranked worst for performance but best in terms of burden. The choice of viewing system depends, then, on the relative weighting of performance and burden. If cost is no object, then the two-view system should be chosen. If burden must be minimized then the mono system is best. There may be a small range in between where either color or stereo is the best choice.

7.8 Use of Proximity Sensors

Bejczy (1976) has demonstrated the use of proximity sensors with display to the operator for remote-manipulation (See Figure 7.19). One of the important variables that determines the value of proximity sensors is the viewing conditions. For a simple block stacking task he found that either "front" or "down"sensors improved performance over mono or stereo viewing alone but that a two-view system showed the same improvement without proximity sensors. That is, you don't need the proximity sensors if you can see well enough. It is interesting that when both "front" and "down" sensors were used simultaneously performance was worse than when either was used alone. This is probably due to the confusion of the auditory display used. Bejczy is now working on a visual display of proximity sensor information (Bejczy and Paine, 1977).

When the proximity sensor information is used by the computer rather than by the operator certain tasks can be accomplished more quickly. For a blind positioning task, Bejczy (1976) found that the computer could stop the arm more quickly and more accurately than could the human operator

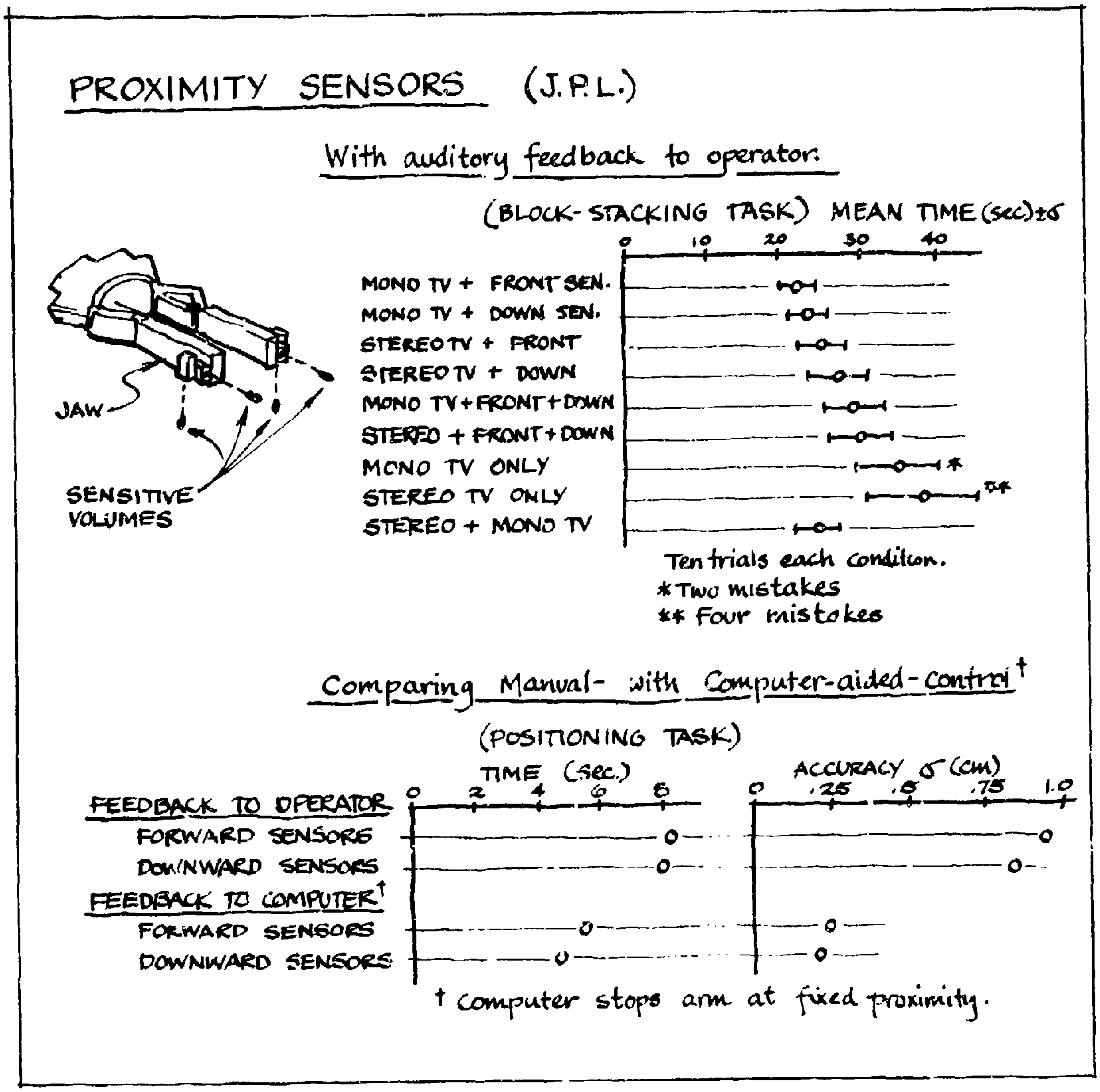


FIGURE 7.19 PROXIMITY SENSORS have been developed at the Jet Propulsion Laboratory (Bejczy, 1976). The results for an auditory display of proximity information are shown at the top. Subsequently, a visual display was developed (Bejczy and Paine, 1977) which allowed greater accuracy.

Computer-aided control, where the computer stopped the arm at a fixed proximity, improved both time and accuracy.

using the auditory display of proximity information (Figure 7.19). It remains to be seen whether this laboratory demonstration will lead to similar applications undersea.

7.9 Evaluation of Computer-Aids; Supervisory Control

The computer-aids to manipulation discussed in chapter 6 were divided into sharing and trading modes.

The only extensive evaluation of the sharing mode has been for resolved-motion-rate-control where the computer does coordinate transformations between the operator's commands (in room- or hand-coordinates) and the manipulator's individual joint velocities. The results have been summarized in section 7.3, showing RMRC to be the best form of rate control.

There have been several demonstrations of the trading mode (Barber, Hill, Freedy, Bejczy) but little data has been accumulated to show under what circumstances the trade to computer control is of advantage.

McGovern (1974) made a detailed study of direct human control in a peg-pick-up task to predict under what circumstances an automatic pick-up program (GROPE) would be faster. Rather than describing human performance with Fitts' law he found that a more convenient and just as accurate representation is to separate motion into a "reach" phase (to within 1/2" of the block) and a "position" phase (the rest). Reach time depends on distance and is independent of tolerance. "Position" time depends on tolerance (B-C) and is independent of distance (See Figure 7.7). The GROPE subroutine was invented and demonstrated by Hill (1973). The manipulator jaw is equipped with touch sensors. The GROPE subroutine takes over control when one of fingers touches. It then increments (a fixed amount, ΔI) until centered on the peg. Thus, GROPE replaces the "position" time.

McGovern showed that GROPE should improve performance only over a small range of tolerances depending on what the movement increment is. (See Figure 7.20). If the increment is larger than the tolerance

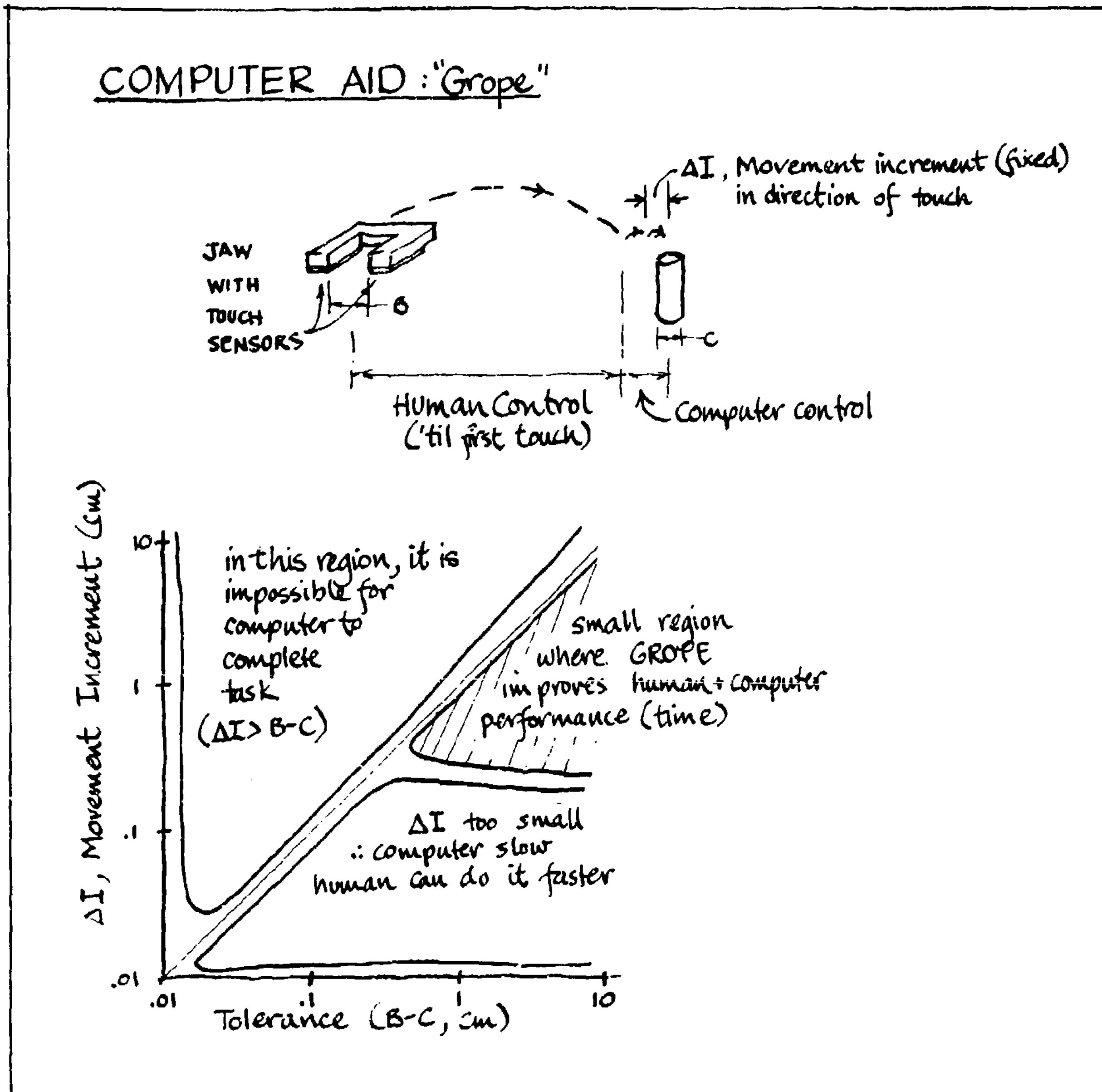


FIGURE 7.20 PREDICTED PERFORMANCE OF "GROPE" SUBROUTINE. McGovern (1974) compared the estimated time for computer controlled positioning (GROPE) to that for manual control (Figure 7.7) and showed that there is only a small range of tolerances (B-C) where GROPE will improve performance. The human vs. computer tradeoff also depends on the movement increment (ΔI) that GROPE uses.

If ΔI is larger than the tolerance, GROPE overshoots; if ΔI is too small, GROPE is slower than the human operator.

the jaw will step too far, missing the peg. If the increment is too small, the computer control will take too many steps and be slower than the human. This theoretically leaves a small region where GROPE may improve performance. Other circumstances (e.g., time-delay, poor picture) may modify these conclusions; also,other sensors or more clever programs may do better than GROPE.

The importance of McGovern's work was demonstration that a detailed look at human performance, with the appropriate summary measures,will be necessary in making decisions about when and how much computer-aiding to use The work of Wernli, et. al. (1978) on the Work Systems Package is similarly appropriate (see section 7.2).

For several years, Freedy, Weltman and others at Perceptronics have experimented with computer-aids to manipulation. One method (Freedy et al, 1971) used was a learning system (ACS) which observed the human operator's motion of the manipulator. If the motion was repetitive enough, the computer could make (with varying degrees of confidence) a prediction of what the next motion was going to be, take over control from the operator, and execute the most likely trajectory. This was an interesting demonstration of computer power at simple pattern recognition but not much use for accomplishing practical manipulation tasks. The operator is seldom interested in repeating the "average" of a series of motions; where repetition is necessary, it is easier for the operator to explicitly show the computer, with one demonstration, what is to be repeated rather than having the computer try to figure it out from repeated demonstrations.

Recent work by Perceptronics is on explicit programming where control can be traded between human and computer. Arm positions can be recorded and returned to with the push of a button (actually a series of key strokes). Laboratory results to date have not shown unequivocally the advantage of trading control with the computer.

The usefulness of such a "go-to-point" automatic subroutine depends on the number of times the point is used and the comparable time for doing

it manually, the time needed to define the point and record the subroutine, and the time it takes to invoke the subroutine (number of key strokes). Perceptronics found one task (valve turning) where "go-to-point" was an advantage, but only if the necessary points were pre-defined. Their results are shown in Figure 7.21. The amount of movement time is considerably reduced by computer control as compared to direct rate control (joystick and toggle switch). But the added time for definition and invocation make computer-aided control no faster. If the "go-to" points are pre-assigned, then there is an advantage to computer-aiding.

For a more elaborate "integrated maintenance task" they found that there was no significant advantage to the go-to-point subroutine. What they concluded was that the task was not repetitive enough (did not use the pre-recorded points enough times), and that the schemes used for definition and invocation were not as convenient as they could be. A revised design for keyboard and syntax has resulted (Shaket,1977).

To properly predict and plan for the use of supervisory control for teleoperation, a full understanding and good data base for direct manual control will be of value. Automatic control should be compared with not just one manual control mode such as fixed-rate switch-control but with the many alternative manual control modes such as resolved-motion rate or position control. One of the difficult choices may be between force-feedback and computer control (between "augmentation" and "automation"). If control is to be traded from manual- to computer-control and back, then the particular form of manual control may be crucial.

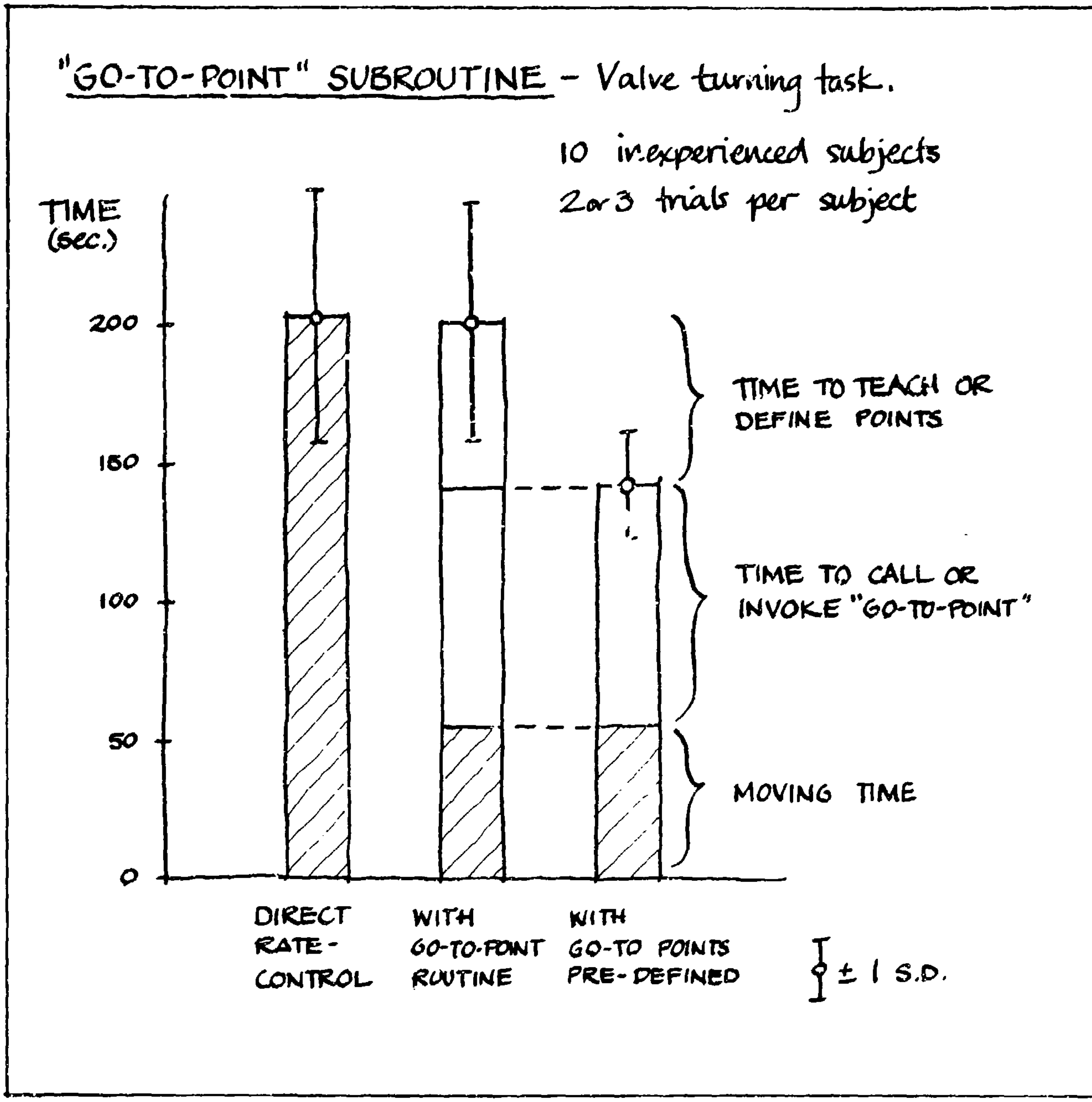


FIGURE 7.21 TIME TO TEACH AND CALL AUTOMATIC SUB-ROUTINES, when added to movement time, may make computer-aided manipulator control no faster than direct manual control.

For a repetitive, valve turning task the "go-to-point" routines only reduced task time when the points were pre-defined. (Berson, et al., 1977).

8. MODELS OF SUPERVISORY CONTROL

8.1 Models and their Uses

A model is a representation of some part of the real world rendered as a scaled (down or up) replica in three dimensions, or a drawing or diagram in two dimensions, or a set of equations or symbolic statements, or a computer program. The model's purpose is to characterize or portray certain salient variables in the real-world situation and the relationships between them, with respect to magnitude and time.

Models are used, then, to describe observed events and to predict future events. Descriptive models are those whose function is to describe, as concisely as possible, relationships between experimentally observed events, with an aim to predicting future events in similar situations, and without a priori regard for a mechanistic or teleological (goal seeking) basis for the relationships. The simplest "black-box" or input-output description is the best. A normative model also seeks to describe and predict experimental events, but it starts from the premise that a certain mechanism is at work, or in the case of a teleological system, that certain goals are sought, or that a certain "objective function" is the basis of optimization or compromise among performance variables. Thus, unlike the descriptive model, the normative model tries to show the degree to which experimentally observed behavior resembles that produced by a given theoretical norm.

Least squares curve fitting, factorial analysis of variance, state determined Markov (transition probability) models, information transmission models, describing functions and other identification models of control systems all tend to be of the descriptive model sort. The theoretical structures used are adapted for describing what happened and from this predicting what will be. They make no presupposition about underlying mechanism or purposiveness of behavior. In contrast, Bayesian models, signal detection models and optimal control models are normative. All constitute ideal norms or perfect mechanisms of behavior with respect to which human or physical system behavior may be compared.

It is commonly appreciated that the choice of model type is made mostly by

art and not science, depending upon the modeler and the tastes of the community of persons to whom he wishes to communicate his research. It is not so well understood that the criterion variables with respect to which models are "fit" to experimental events are similarly chosen. Below are listed different kinds of criterion variables which are commonly used to fit models to experimentally derived data from man-machine systems:

1. degree to which model's behavior produces same overall or final "success" as observed system
2. degree to which model's behavior produces same success in component tasks
3. degree to which model makes same set of responses, independent of time or order
4. degree to which model produces same sequence or trajectory of response states, independent of time
5. degree to which there is a response correspondence at each point in time
6. degree to which subjective ratings by human observer are same for model and observed system

The dilemma is that, given the same basic model and same empirical data, different parameter coefficients will be best fits depending on which fitting criterion is chosen. Ideally a model should provide a perfect fit to the corresponding experimental data for every variable it simulates. In practice this is not realistic, due in part to limits on time and money for developing models and limits on complexity for what can be understood and put to work by the user.

8.2 Modeling Teleoperator Control, especially Supervisory Control of Teleoperators.

Probably the most difficult part of the teleoperator control modeling is the manipulation aspect. Insofar as remote vision, communications and vehicle control are considered part of teleoperation, there exist corresponding modeling sub-disciplines which are reasonably well developed and applied, namely signal detection and pattern recognition, information theory, and conventional control theory, respectively. This is not true of manipulation.

One might think of manipulation as modelled with control theory, or some mixture of same with classical mechanics and the theory of automata (computers). To affirm this is to affirm hopes and aspirations, for our theoretical understanding of how to model the mechanics and control of grasping, moving and assembling objects is primitive indeed. Manipulations are discontinous in time and space. One can stop an assembly or disassembly task in the middle and go back to it, provided enough static friction exists. Also, there are logical sequential contingencies inherent in manipulation: the tool must be located before it can be grasped, grasped and positioned before it can be used on another object, etc.

Differential equation models of control theory don't adapt to these logical contingencies. But computer programs easily adapt to such contingencies <u>and</u> can simulate continuous Newtonian mechanical interactions. The problem is that such simulation models tend to be very complex, with many degrees of freedom - "identification" or convergence upon parameters, or "solution" in a closed-form sense is very difficult. Modeling the behavior of a teleoperator system is not unlike modeling the motor skills of a person; the inherent difficulty of the latter is an old story to the experimental psychologist.

When an active computer is added and the human operator becomes a supervisory controller, the modelling task obviously takes on new dimensions and new problems. It is appropriate that the models of supervisory control strive to characterize (and predict) those aspects of man-machine behavior which are unique or at least different (as compared to teleoperation in general) - such as what tasks the computer can do best, and what performance may be expected from human operator vs. computer using a common measure, when the human operator does or should turn control over to the computer and vice versa, what difficulties are experienced by human operator and computer in communicating with the other.

A key question which models might help answer is when supervisory control is necessary (or better than non-supervisory control, or economically justifiable, etc.). As we have previously suggested, computer automation is obviously advantageous on the production line where the same task is being repeated precisely. A preprogrammed device can move faster and with more precision when the environment is known. But where is the advantage of computer control in undersea tasks? We

think the answer lies in the fact that <u>some</u> elements of the task geometry, etc., are usually known ahead of time and therefore <u>some</u> preprogrammed elements can be called up usefully in almost any task. Others, of course, are encountered afresh, and ingenuity and human judgment must be brought to bear to cope with completely unanticipated events. For example, if holes must be drilled or tapped, tools must be exchanged, cleaning of surfaces or scanning with instruments must take place - these operations must occur mostly in a manner which can be anticipated - except for locating and orienting the manipulator (sensor) relative to the environmental object. Thus, once this manual location and orientation activity is accomplished, the automatic routines can be called, with prospect of considerable savings in time and errors relative to doing the <u>whole</u> job manually. Models are needed to generalize on experiments to help decide how and when to give control to human vs. computer.

Figure 8.1 offers a way to organize our discussion of models currently of promise for various aspects of teleoperation, expecially supervisory control of teleoperation. This flow chart suggests four different levels at which decisions are made, each including a test following the corresponding decision activity which is a basis for commencing operations at the next lower level. At the lowest or most primitive level (A) decisions are made to "sense and act" quickly. Such decisions are either computer program controlled or they are perfunctory rate or position servoing by the human operator. At this level feedback is essentially continuous. At the next higher level (B) are supervisory control decisions and tests. These are mostly human, though sophisticated supervisory systems may include computer aids, especially in testing whether programs are appropriate before they are committed to actions. Feedback is intermittent, with time constants of seconds and minutes. At the highest two levels (C,D) decisions are for allocation and design, and tests are almost always human. Models, as suggested earlier, can be used to describe and predict events at each of these four levels. Because the events at A are quite different from those at B, and those at C and D (taken together) are quite different in turn, we have chosen to separate models into these three categories.

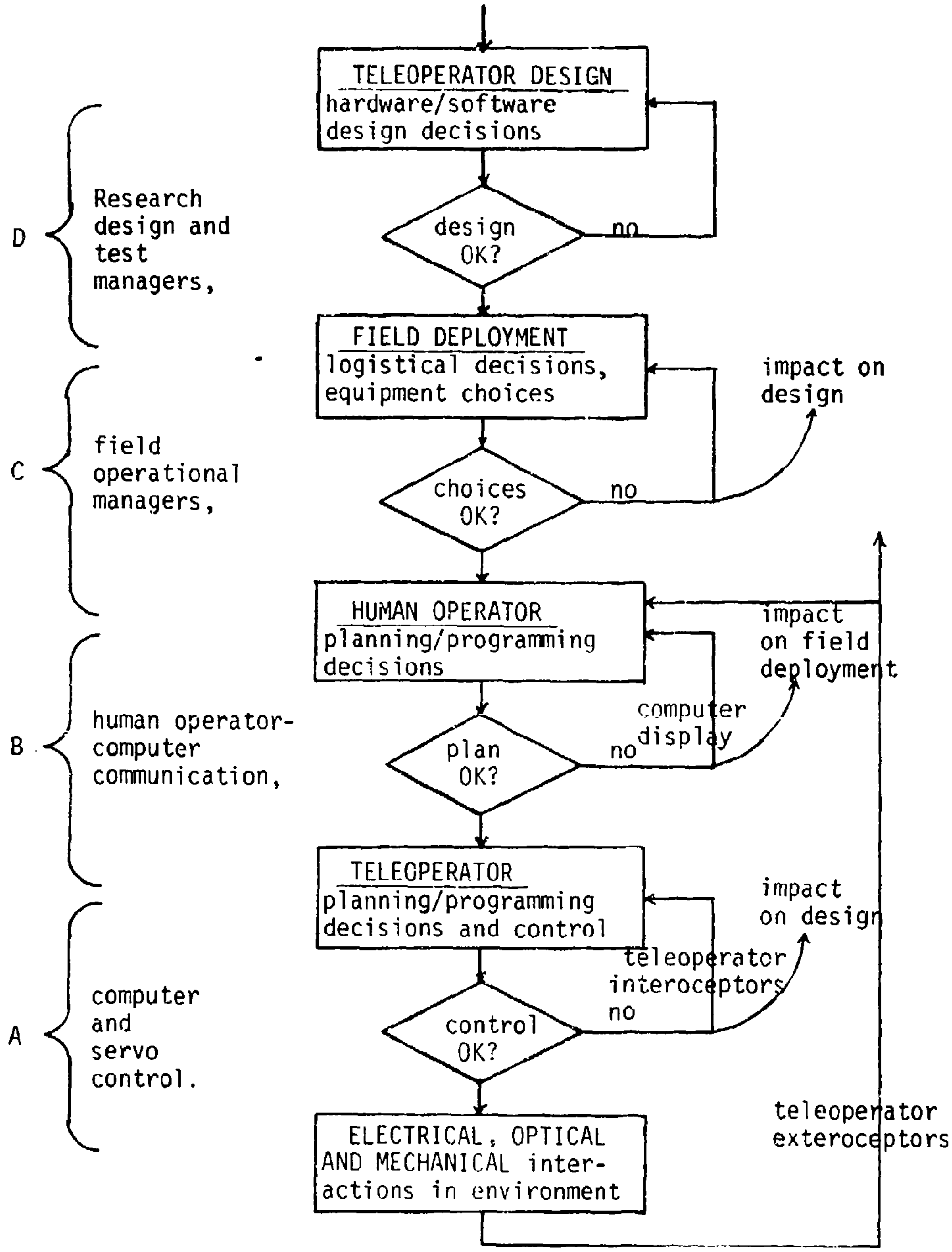


FIGURE 8.1 LEVELS OF DECISION MAKING AND MODELING IN TELEOPERATION. At level A decisions and models are for seeing and acting in terms of physical interactions at the manipulator-environment interface. At level B decisions and models regard communication at the man-computer interface. At the C level decisions and models are for planning and allocating teleoperator resources to do specific missions. At the D level decisions and models are for purposes of designing those teleoperator systems.

8.3 Modeling Teleoperator System Performance at the Environment Interface (level A)

The purpose of a teleoperator is to manipulate and/or sense objects in the environment. The key variables at this interface are the space, time and force (and energy) components of this continuous time interaction. Thus the purpose of models of this interaction is to predict such space, time and force events - given the task manipulation and control configuration, etc. At this interface whether a teleoperator system does or does not incorporate supervisory control can be a contingency or parametric constant in the model, but it need not be made a variable.

The idea of the Weber fraction for sensing or motor action is an old and still viable model: the probable error (of distance, time) in positioning movements is roughly a constant fraction of the magnitude of the corresponding variable, down to relatively small movements.

Breaking motor responses into gross positioning motions followed by fine adjustment motions is also an old idea. The "scientific management" proponents of the 1930's (Taylor, Gilbreth) developed a rather elaborate classification of manipulations (hand-object interactions), including "grasp", "transport loaded", "transport empty", "position", "preposition", etc.

Following Shannon's development of information theory in the late forties, (Shannon and Weaver, 1963) Fitts (1954) showed how the logarithmic measure of the ratio of move distance to error tolerance made a simple but useful predictor of the move time. This measure ($\log \frac{\text{move distance}}{\text{error tolerance}}$) also came to be known as "Fitts' index of difficulty". This was discussed in detail in Section 7.

Ferrell (1965) showed how Fitts' index could be used to predict how many "open loop" moves a human subject requires, when there is no feedback, to move a certain distance to within a certain tolerance. He went on to show how the number of open loop moves when there is no delay can be used predict task completion time when there is a pure transmission time delay in the control loop.

A closely related application of information theory is the prediction of response time as a log function of the number of equiprobable response alternatives to be selected among - the so called "disjunctive reaction time".

Combining a stimulus set of events of differing probabilities with a set of response alternatives with differing probabilities and required movement to within a given tolerance, one might obtain a crude predictive model.

But in doing assembly in multiple degrees of freedom, even with manipulating but one rigid object (say a peg) to achieve a final state relative to fixed environmental contraints (putting it in a hole), the Fitts' law idea can easily break down. The reason is that reduction of uncertainty does not normally proceed simultaneously in all degrees of freedom. Further, there are special nonlinearities encountered, such as the "binding" phenomenon investigated by Whitney (1978) as a function of angle of approach, peg and hole (and tolerance) dimensions, etc. Whitney's models predict "binding" or "jamming" situations rather nicely based simply on kinematic criteria.

Classical dynamic models of manipulators can be important both in predicting oscillations (which tend to be worst with arm fully extended and when sudden movements are made) and as a basis for determining time-optimal or energy optimal trajectories to move the arm from one configuration to another. Typically the dynamic limitations of the manipulator per se do not by themselves seem to limit performance; in undersea situations it is usually the operator's ability to see and control precisely which sets the limit on accuracy of positioning for a given time, or of time required to position to a given accuracy. Sensory threshold nonlinearies added with a simple control loop model can help predict such performance limits.

In any motor skill task, and this is necessarily true of teleoperator control, a compromise must be reached between time, accuracy, reliability (errors) and effort. A simple model of this trade-off is a set of linear constraining relations (which can be graphed as planes in hyperspace, lines if only two trade-off variables are included such as are shown in Figure 8.2). For each variable there may be some absolute constraints (i.e., no matter how much time or effort is spent, accuracy can be no better than some hysteresis constraint or visual error; no matter what accuracy is accepted some minimum reaction time is required). Given such a bounded space of possible solutions, the best or normative linear pro-

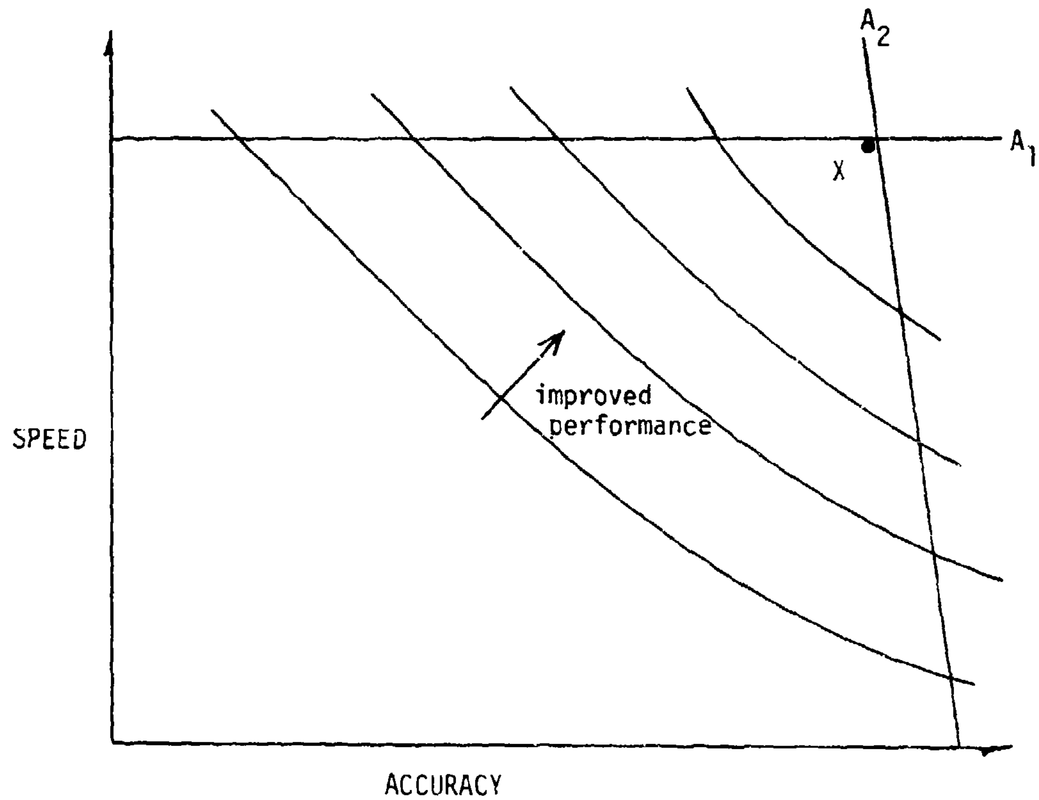


FIGURE 8.2 SIMPLEX LINEAR PROGRAMMING EXAMPLE FOR OPTIMIZING A TELEOPERATOR. Given a set of performance tradeoff curves for speed and accuracy, the farther to upper right the better. Given a set of absolute constraints (e.g., maximum slewing speed is line A_1, speed-accuracy vibration limit is line A_2), then X is optimal point.

gramming model is that point having the maximum value on a set of tradeoff curves (i.e., the objective function). This is called a "simplex graphical solution". When dynamical constraining equations obtain, a dynamic programming solution becomes necessary.

Thus far the models described apply equally well to direct and supervisory control. What is it at the A level interface which is different between direct manual and supervisory controlled teleoperators? One difference is that when in the supervisory mode significant "dead times" appear at the output while the operator is reprogramming. Thus, in terms of the completion time variable alone, as a function of some "task complexity" attribute (Figure 8.3), at some degree of complexity supervisory control will prove superior to direct manual control.

When it comes to accuracy of performance direct manual control may be counted on to have some minimum probable error, but never be grossly in error. The supervisory system, on the other hand, can easily be more precise when it has been programmed properly and environmental contingencies turn out to be as anticipated or have been allowed for in the program (which branches and adapts based upon the teleoperator's own sensors). But occasionally the computer, due to its own failure or due to human error in programming it, will make spectacular errors, comparable to industrial robots which proceed with apparant precision to assemble parts which are never picked up, or to spot weld the thin air.

8.4 Modeling Human Operator Behavior at the Computer Console Interface (level B).

Unlike models at level A which focus on the continous manipulator/sensor-to-environment physical interactions, models at level B focus on the more or less discontinuous communication between man and computer. Such communication, of course, is not present in direct manual teleoperator control in a rate or master-slave mode. For the latter by itself the A-B level differentiation has little point.

A first category of man-computer interaction to be modeled is the use of the computer in planning, off-line and disconnected from the teleoperator. A use-

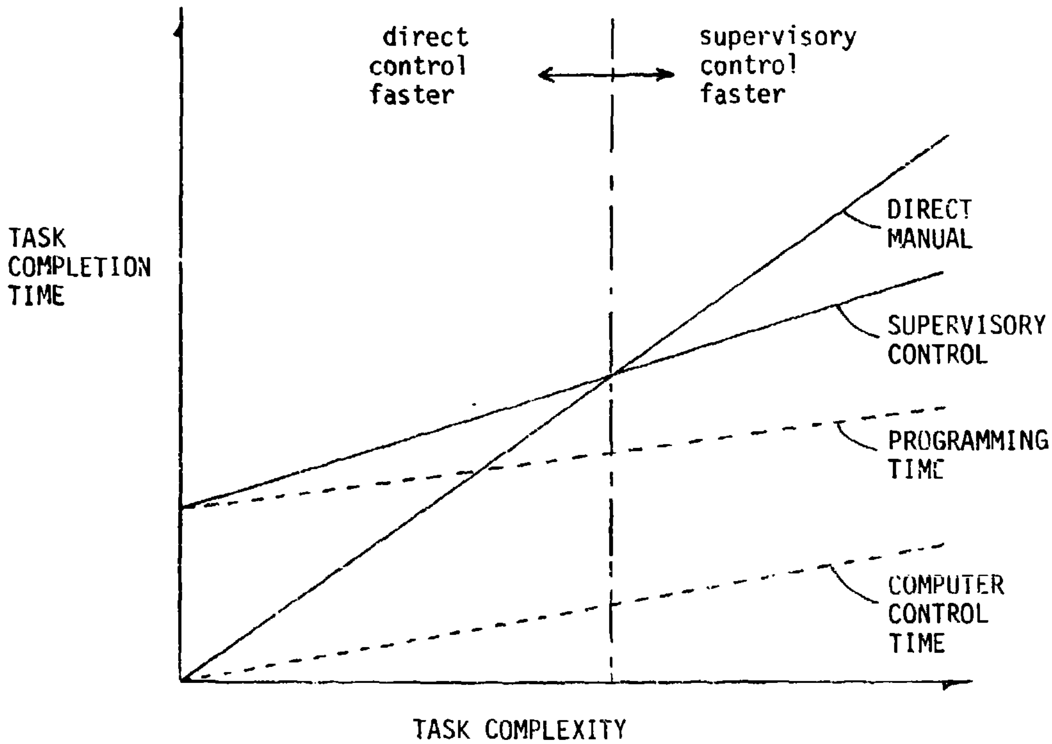


FIGURE 8.3 HYPOTHETICAL TASK COMPLETION TIMES AS A FUNCTION OF TASK COMPLEXITY. In direct teleoperator control completion time rises smoothly with task complexity. In supervisory control an initial programming penalty is paid on each move no matter what the task complexity, but for more complex tasks there is a real advantage.

ful model should help compare the computer with other (non computer-based) planning aids used in supervisory control, including no planning aids at all. There can be several meanings of "model" here:

1. representations of how an analyst structures the task using diagrams such as the Sacerdoti "procedural net", state transition diagrams, logic flow
2. representations of how the operator thinks of his task as gleaned from interviews and "verbal protocol" descriptions (precendence diagrams, task time-lines, goal hierarchies)
3. how the operator does, or might use, a computer-based "internal model" for trial and error thought experiments, or as a prediction display of future events extrapolated from present conditions, etc.
4. how other representations or memories within the man-machine system are used by the operator, in conjunction with his own "in-the-head" internal representation of the task and the current state of the system (2 above); and a computer-based internal model (3 above). Such additional representations can be embodied in the current configuration of a replica controller or the current status of a display. Figure 8.4 points out the variety of such "internal models" the operator has available.

Probably the most important kind of (external) model at this level is that which characterizes the operator's programming and control decisions - what he commands the computer to do and what he controls himself. Such models would seek to predict:

1) what part of task the operator chooses to do manually, what part he programs for the computer to do
2) what commands he selects from among those available
3) in what order or with what contingencies he assembles these
4) how long a string of commands he assembles (how far operations are programmed open loop, i.e., without feedback). There is an analogy to signal detection theory which seems to apply here which balances the marginal progress in one successful program against the increasing risk of failure as the program becomes longer.
5) what balance he makes between sensing and motor activities in specifying

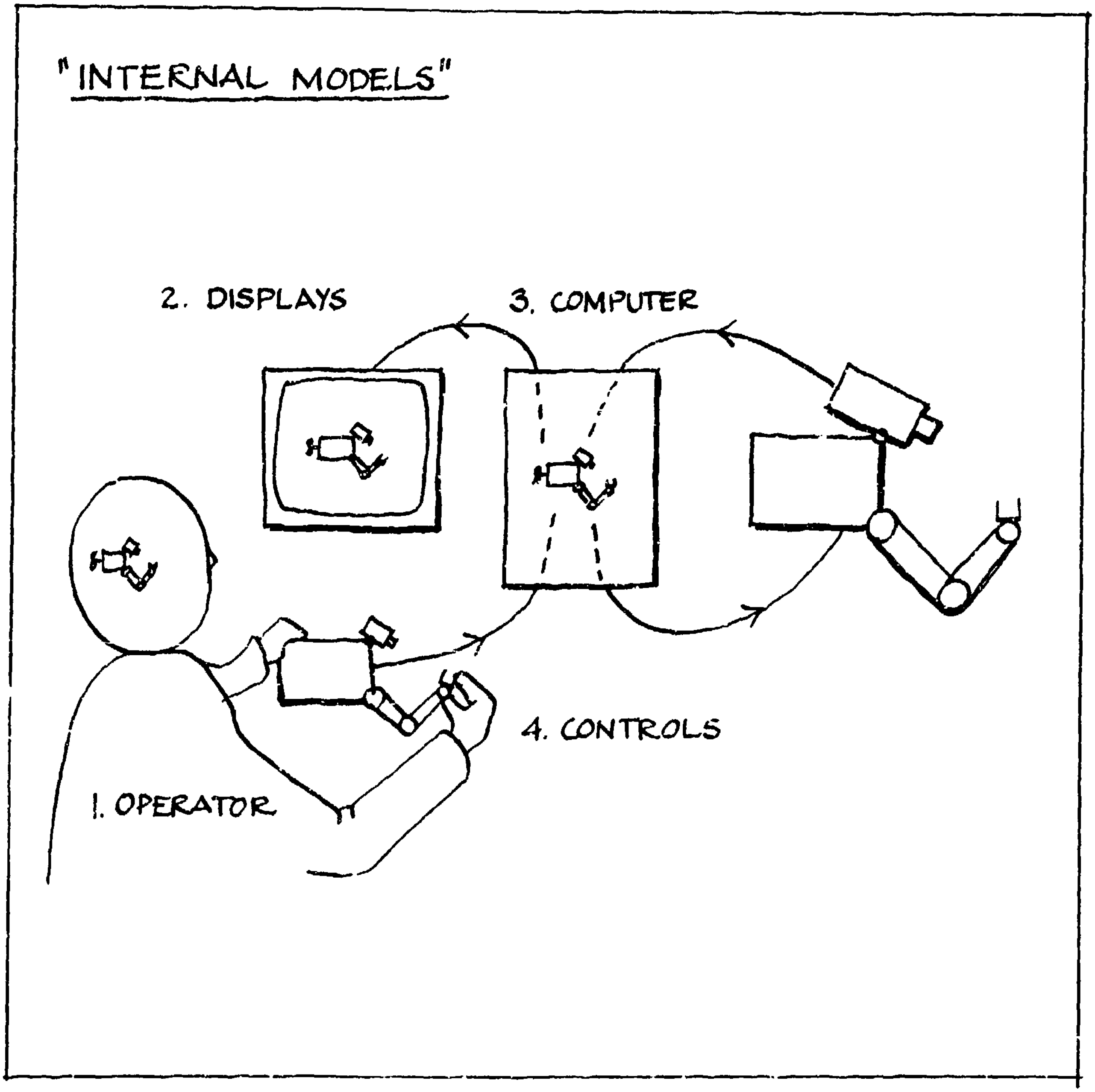


FIGURE 8.4 LOCI OF "INTERNAL MODELS" IN A TELEOPERATOR SYSTEM. Each numbered location in one way or another represents the state of the system, is updated either by the operator or by the hardware/software, and is referenced by the operator in planning and controlling.

commands. The "optimal stopping" model fits here - normatively determining a compromise point where taking more data to better understand the problem reaches a point of diminishing returns, where it is time to start action before it's too late.

6) how long it takes the operator to write such a program
7) how many and what kinds of errors he makes in programming
8) what procedure the operator uses for discovering and debugging an inappropriate string of commands, i.e. commands which the computer rejects
9) the extent to which the operator's decisions and pace are determined by: (a) a nominal plan and schedule; (b) conditioning from training or by other experience; (c) ongoing rational decisions about what to do and when.

After the operator turns his program over to the computer to run he must monitor its execution. Deciding when to sample the input and when to reset the controller may be modeled in terms of information value theory (Sheridan, 1970) which presupposes an internal autocorrelation model of input events plus (possibly) a fading memory on the part of the operator.

Deciding when a particular program has gone awry closely resembles the problem of detecting a change in process dynamics in manual control. Thus human recognition performance can be modeled on the basis of on-line process identification (as has been used in manual control), but more satisfactorily (in the teleoperator context) modeled as a statistical deviation between observed response and that of an internal dynamic model (as certain failure detection models do).

An interesting experimental question is whether the human operator can detect a teleoperator failure better, or decide on a better way to handle a current situation, when he is an active manual controller or when he is a passive observer. In the manual control (aircraft) area there is conflicting evidence (Curry, 1976).

Another type of man-computer interaction consists in the operator taking over control from the computer, either when it has completed its task or in an emergency. This can be done by a signal to the computer to execute a program which interrupts present action if necessary, and returns the manipulator to a "safe" take-over configuration. Alternatively it can be accomplished by instantaneously connecting the operator's rate or master-slave hand control to the manipulator. Modeling this recovery situation will be useful in comparing the slower and more orderly (but possibly inadequate) first method with the abrupt, erratic second method which nevertheless may be more apt to avoid severe error.

Thus models at this level explicitly represent the trading and sharing of control between human operator and computer, and the transitions from planning to programming to monitoring to human takeover. Graphical techniques such as were described in the chapter on task analysis - flow charts, transition frequency charts, etc. - are appropriate here.

8.5 Modeling to Decide How to Allocate Resources, Design Hardware and Software (levels C, D)

Models at this level step back still farther and consider systematically how different hardware and software configurations might have differential effects on operator and system performance, either from the viewpoint of what is put together for a given mission, or what is designed in the first place.

The independent variables of such models are the equipment parameters of

1. hardware
   a. sensors (range, resolution, etc.)
   b. arms (size, accuracy, speed, power, kinematics and anthropomorphism)
   c. operator console and display - how specialized, what form of control
   d. maintainability
2. software
   a. command language elements, structure
   b. speed and accuracy of sensing and control
   c. alarms, alarm strategy
   d. back up options
   e. on-line models for control
   f. on-line planning aids
   g. on-line aids for training

The "models", then, are tables, diagrams or analytic or computer-based methods for stating what effect the inclusion of certain hardware or software features, or more or less automation, or better or worse quality of any such component, might have on system performance or human behavior at the man-console interface. Models at this level would explicitly compare different mixes of human and computer decision making.

Tables 8.1 and 8.2 give an example. A sequence of six "decision sub-elements" in Table 8.1 is assumed to apply to most man-computer decisions. But there is a variety of ways in which man and computer can cooperate. Table 8.2 orders these as "levels of automation" going from a level wherein the human operator does everything to a level where the computer does everything. Clearly as more automation is introduced some benefits accrue, but concomitant risks are also incurred. The model can help the designer or operational manager decide what mix of man and computer to use.

At this level subjective judgment of operators or observers can be used to advantage. There are various qualities of the situation which can be modeled as judgment profiles, such as:

1) handling qualities (responsiveress and controlability , interface transparency, naturalness, dexterity, flexibility, gracefulness in failure, etc. as suggested inthe previous section).
2) operator mental workload

Judgment data can be aggregated and scaled on single-dimensional scales or using multi-dimensions. There are different "judgment heuristic" techniques by which such subjectively based models can be generated (Sheridan, 1978). These include:

1) simple category scales of a given quality
2) utility theory (with single or multi-attributed arguments), which forces judges to scale on a ratio basis, such as "I'd be indifferent between x for sure and a 50 - 50 chance of y or z"
3) policy capturing, which assigns overall weights directly to various points in multi-attribute space and uses linear regression to specify the relative effects of various levels of different attributes

TABLE 8.1

BEHAVIORAL ELEMENTS USED TO CHARACTERIZE DEGREES OF AUTOMATION IN MAN-COMPUTER DECISION-MAKING

OPERATORS COMBINE WITH:	OPERANDS FOR HUMAN (control coding)	OPERANDS FOR COMPUTER (display coding)
REQUESTS (asks from other party)	options SELECT action TELL action	
GETS (fetches what is requested or necessary)	options	options
SELECTS (chooses from among options for intended action)	action	action
APPROVES (agrees or disagrees with a particu ar decision)	SELECT action START action	START action TELL action
STARTS (initiates implementation)	action	action
TELLS (informs what was done)		action

TABLE 8.2

LEVELS OF AUTOMATION IN MAN-COMPUTER DECISION-MAKING

for a single elemental decisive step

DESCRIPTION OF INTERACTION	HUMAN FUNCTIONS	COMPUTER FUNCTIONS
1. human does the whole job up to the point of turning it over to the computer to implement.	(GETS options from outside) SELECTS action STARTS action	
2. computer helps by determining the options	(REQUESTS options) SELECTS action STARTS action	GETS options
3. computer helps determine options and suggests one, which human need not follow.	(REQUESTS options) (REQUESTS SELECT action) SELECTS action (can be different) STARTS action	GETS options SELECTS action
4. computer selects action and human may or may not do it.	(REQUESTS options) (REQUESTS SELECT action) APPROVES SELECT action STARTS action if HUMAN APPROVES	GETS options SELECTS action

DESCRIPTION	HUMAN	COMPUTER
5. computer selects action and implements it if human approves	(REQUESTS options)	
		GETS option
	(REQUESTS SELECT action)	
		SELECTS action
	APPROVES START action	
		STARTS action if HUMAN APPROVES
6. computer selects action, informs human in plenty of time to stop it.	(REQUESTS options)	
		GETS options
	(REQUESTS SELECT action)	
		SELECTS action
	APPROVES START action	
		STARTS action if HUMAN APPROVES or if t > T and HUMAN HAS NOT DISAPPROVED
7. computer does whole job and necessarily tells human what it did.	(REQUESTS SELECT action)	
		GETS options
		SELECTS action
		STARTS action
		TELLS action
8. computer does whole job and tells human what it did only if human explicitly asks.	(REQUESTS SELECT action)	
		GETS options
		SELECTS action
	(REQUESTS TELL action)	STARTS action
		TELLS action if HUMAN REQUESTS

DESCRIPTION	
9. computer does whole job and tells human what it did and it, the computer, decides he should be told.	(REQUESTS SELECT action) ↘ GETS options ↓ SELECTS action ↓ STARTS action ↓ TELLS action if COMPUTER APPROVES ↙
10. computer does whole job if it decides it should be done, and if so tells human, if it decides he should be told.	(REQUESTS SELECT action) ↘ GETS options ↓ SELECTS action ↓ STARTS action if COMPUTER APPROVES ↓ TELLS action if COMPUTER APPROVES ↙

Note: There are other variations possible. For example, in each of the ten steps the original human request may either not be necessary or be ignored by the computer. Step 10 can have several variations where it tells the human necessarily, or on his request, or etc.

4) Thurstonian scaling, which rescales raw data along a continuum based on discriminal dispersion (relative spread) of the judgments for a given object or event
5) multi-dimensional scaling, which utilizes a matrix of "dissimilarity judgments" between objects or events to identify the principal axes with respect to which dissimilarities are perceived
6) interpretive structural modeling, a scheme to order pairs of objects or events with regard to some diadic relation (e.g., "should be done sooner than", "affects the control of") which presupposes consistent transitivity of judgments and thereby obviates the need to make all possible pair comparisons.

The value judgements from individuals, and their aggregation into "social choice" models of group values, are especially important in dealing with policy questions, such as when should the computer be enabled to overrule the operator. No general answer to the latter question is available for now; there are examples of both human authority over computer and computer authority over human in various complex and high-risk man-machine systems.

9. RESEARCH NEEDS FOR MAN-COMPUTER CONTROL OF UNDERSEA TELEOPERATORS

This Section summarizes what are believed to be primary research needs for man-machine control of undersea teleoperators. All of the needs cited have been implied in the foregoing sections; they are presented here only in capsule form.

9.1 Task Analysis and Performance Measurement

In view of the close relationship between task analysis and performance measurement of teleoperators, the research needs in these two areas are combined. Moreover, because tasks and the tools to do them must be matched, research is necessary to further clarify this task-teleoperator matching relationship.

1. Continuing efforts are needed to define and classify undersea tasks of the kinds which might be amenable to teleoperation, (although it is clear that such taxonomies will evolve as missions evolve and as teleoperator technology changes what is achievable by teleoperation). Data on both sequential contingencies and distributional frequencies should be compiled. Since much of what now passes for task analysis is compilation of anecdotal data, there is a clear need to observe, measure and record more objectively and precisely what is now done or attempted by divers or teleoperators.

2. From an operational viewpoint improved methodology for analysis of specific undersea missions (e.g., search a certain ocean area, find and retrieve a particular downed aircraft) and specific tasks (e.g., secure a net around fuselage) is important in order to decide:

- what, if any, teleoperator system to employ, or if a human diver is better
- what "tool kit" should accompany the teleoperator
- what kind of planning and preparation to do and what are the support logistics
- how long the mission is likely to take
- what are the dollar costs
- what are the risks to human life, failure of mission, damage to equipment, etc.

3. Improved models should be developed for the physical interactions between teleoperator sensors and manipulators and the objects they sense and manipulate. Theories of pattern recognition,signal detection, and others are being applied to sensing. There is little or no suitable theory of manipulation, including both mechanical dynamics and control logic, available.

4. In cooperation with Navy and industrial users, vendor companies and the research community, an accepted battery of laboratory tests should be developed which incorporates a broad range of features of "real" undersea tasks. These tests should be quantitatively adjustable or calibratable with respect to size, force, tolerance, speed, accuracy, etc., required. They should quickly yield a profile of scores on salient objective performance variables.

5. Subjective measures of the quality of various phases of teleoperator control (sensing, command programming, continuous manual control, task execution) should also be developed.

When enough test data are accumulated reliability analyses should be performed, including both human operator and teleoperator equipment components.

6. Since teleoperators can be either more general-purpose or more special-purpose, research is needed to determine when the "point of diminishing generality" is reached, assuming generality increases cost of one teleoperator.

9.2 Man-Computer Communication

1. When a computer is used in an undersea teleoperator system for other than real-time aiding of sensing or control, i.e., when there is trading of control between human operator and computer, smooth man-computer communication is crucial. The sparse evidence available suggests that when this communication is awkward supervisory control of teleoperation is inferior to direct manual control, but when man-computer communication is good supervisory control can be faster and more precise. This advantage of supervisory control is especially present when the communication channel

to the teleoperator is degraded. Not only can research in this broad area be of great advantage to improved design of teleoperators, but, because of the generality of the problem, it can benefit understanding of man-computer communication in general.

2. The man and computer must understand what each other knows and is intending to do. Each may be said to have an "internal model" representing the current state of the system and its environment. The state of the sensors and displays and the state of the controls are also available models or representations of current knowledge. Some research should aim to understand how man and computer do or could access each other (plus other "models"), test their own knowledge, modify their own or update the other's knowledge.

3. We need experiments to determine how people structure knowledge about everyday inspection and manipulation, how they naturally tell other people how to accomplish such tasks or describe environmental states, what metaphors, nouns, verbs, modifiers, syntax they use. We need experiments to determine how people perform when their means for communication about such task procedures and environmental states is constrained or modified, i.e., they are restricted in their symbolic statements or analogic commands. Such information can then be used to devise computer knowledge structures which best adapt to teleoperator control and accord with human ways of structuring knowledge about inspection and manipulation.

4. The computer may perform automatic routines to search, avoid obstacles, accommodate (make fine adjustments to fit together two mating parts and not bind),resolve end-point motions, exchange end-effector tools, move in a pattern so as to keep a fixed distance from a surface or a fixed orientation relative to some reference frame,etc. Beyond "demonstration of special capabilities", research is needed to show when these capabilities save time over direct manual control, under what circumstances the operator prefers to use them at the (possible) cost of extra communication burden, and what the risks of failure are.

5. "Trading" and "sharing" as discussed earlier in this report are very different modes of working with another human being. What are the fundamental behavioral traits of man or computer which militate in either direction for particular types of task? This is a long range research need.

6. Research should be done to understand when the computer activity should be "transparent" to the operator (control "sharing" situations where only the result of computer processing is most important) and when the computer activity should be apparent to the operator (control "trading" situations where computer is being monitored or its misbehavior is being diagnosed).

7. Some continuing research effort should be devoted to better means to teach sensors how to search or manipulators how to perform using combinations of analogic and symbolic commands. Should symbolic commands be dedicated keys or be strings of general purpose keys, or some combination?

8. A persistent research question concerns when the human operator should have authority over the computer and when the computer should have authority over the human - and on what time scale.

9.3 Sensing and Display

Though sensing and display research for undersea applications is active and ongoing, there are some research areas pertaining especially to man-computer teleoperator control.

1. One research opportunity concerns the tradeoff between video (or sonar) frame rate and resolution, which is especially critical when the bandwidth is low. The computer can allow for an adjustable tradeoff, so that the operator can have a more or less continuous but low-resolution picture for one phase of his task and a very occasional high-resolution picture for another phase.

2. Limited frame rate, when combined with significant transmission time delay (such as occurs with a sonic communication channel) can pose severe problems in control. One solution is the "predictor display" (discussed in Sections 5 and 7). Research is needed on performance with predictor displays for various delays, frame rates, process dynamics and other factors.

3. Computers can aid teleoperator displays in various other ways. Superposing sonic and video images might be an advantage in turbid water. Super-

position of computer-generated alphanumeric or graphic information over the otherwise conventional video display can preclude unnecessary eye scan (much as an aircraft "head-up" display). Predictor information could be superposed on the video picture, as could sonar range information.

4. "Teleproprioception" was discussed at length in the report , and we feel it warrants considerable further research beyond the sometimes discouraging efforts at head-mounted displays, etc. Computers plus storage tubes can provide the operator a wide-angle "local model" derived from previous sweeps of a narrow angle video camera or a side-scan sonar. Replica controllers can serve not only for on-line control but for trial runs relative to "local three-dimensional models". Most important for research are: (1) a better theoretical understanding of "teleproprioception", and (2) a better empirical data base to specify how performance degrades as correspondence between remote arm, sensor and vehicle and local counterparts (arms and sensors on both operators' body and video display) degrades.

9.4 Continuous Control

There are a great many questions regarding continuous teleoperator control still deserving of research effort. Among these are:

1. Usually at least some degrees-of-freedom of control of the submersible vehicle are redundant with degrees-of-freedom of the manipulator arm. With a six-degree-of-freedom arm and six-degree-of-freedom vehicle control there would be complete redundancy. Under what circumstances should redundancies be eliminated and the vehicle propulsion system be used by the operator to guide the arm?

2. Speech recognition and speech production are now technologically available. Can they improve human control of a teleoperator?

3. A "replica controller" in conjunction with a computer can be used as a position controller within a given envelope and a rate controller outside this envelope (see description of the M.I.T. SUPERMAN program in Section 6).

Some degrees of freedom of the replica can be programmed to provide position control while others provide rate control. Under what circumstances are such "mixed modes" confusing to the operator and what are their advantages?

4. Force reflection is now available on some undersea manipulators, but we still have little understanding for which tasks and for what degrees of freedom force reflection is important. By adding force reflection to some manipulator degrees of freedom, and only brakes or locks to the other degrees of freedom, can the same effective capability as with full force reflection be had at lower cost and complexity?

5. Manipulators tend to have constant damping for a given velocity, based on passive damping counterbalanced by rate feed-forward. They could be provided adjustable impedance characteristics to allow, for example, the operator to program free ballistic (undamped) motions at the beginning of large excursions and heavily damped motion at the end or for fine adjustments. Would this be an advantage?

6. Most manual control research has been done with linear dynamic processes. Teleoperators present classical nonlinearities about which there is still a dearth of man-machine dynamic modeling based on experiment. Some such nonlinearities are static fr ction, backlash, servo-bias, gravity droop (arm extended), slewing rate limits, and time delay. Sometimes added dynamic constraints may help compensate for nonlinearities (e.g., small vibration may overcome static friction, viscoinertial lag may prevent time-delay instability).

7. Finally, research is needed on computer-control strategies for "fail-soft" abortions in case there is evidence that the control loop has been opened for more than some threshold period, or some human input is obviously called-for and not forthcoming. These may continue the same activity at a lower level, may force retreat to a safety position, may stop and "hold", or stop and "relax", or may begin execution of a complex return and recovery activity.

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